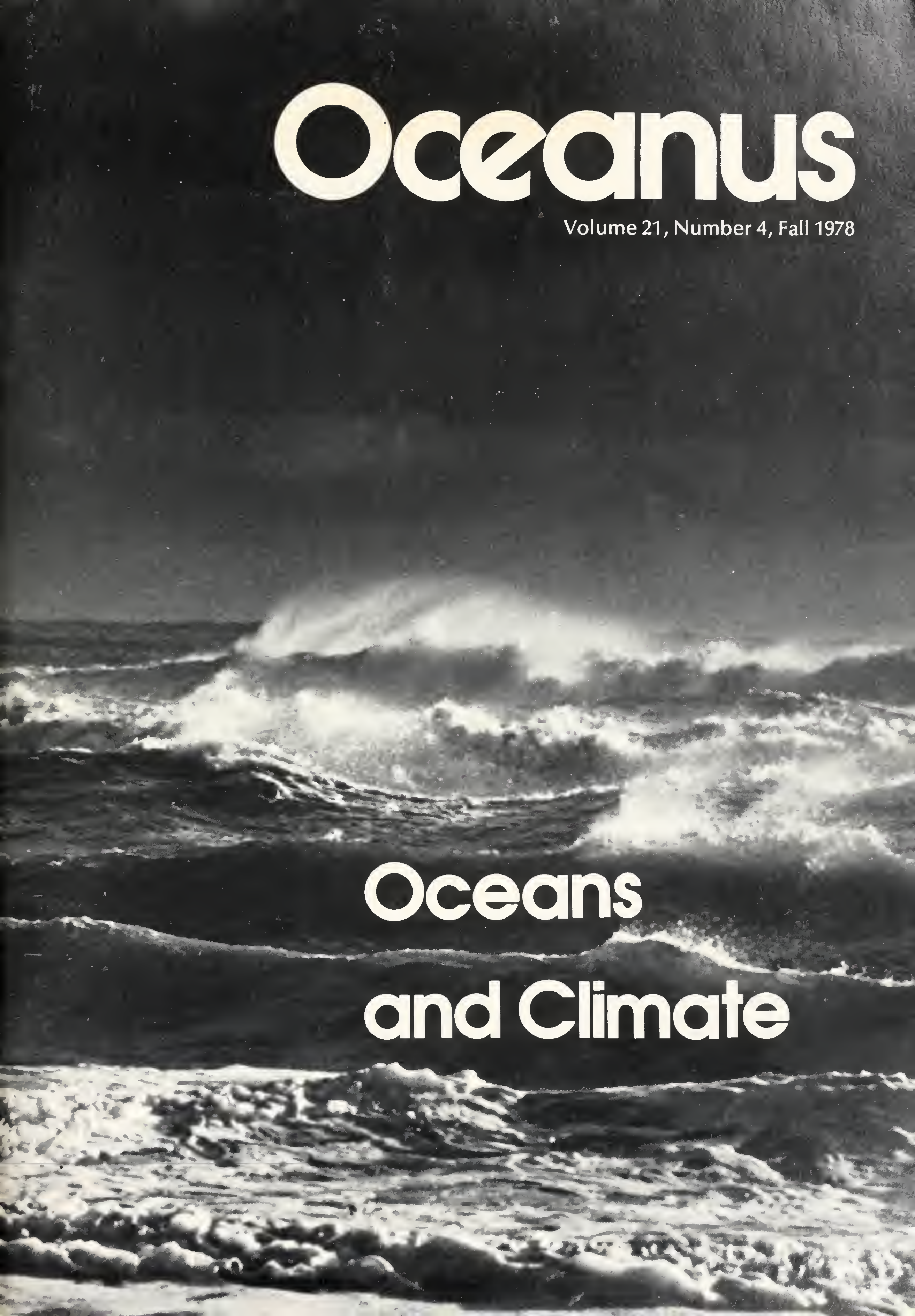
Oceanus

Volume 21, Number 4, Fall 1978



Oceans and Climate

Oceanus®

The International Magazine of Marine Science

Volume 21, Number 4, Fall 1978

William H. MacLeish, *Editor*
Paul R. Ryan, *Associate Editor*
Deborah Annan, *Editorial Assistant*

Published by Woods Hole Oceanographic Institution

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The views expressed in *Oceanus* are those of the authors and do not necessarily reflect those of Woods Hole Oceanographic Institution.

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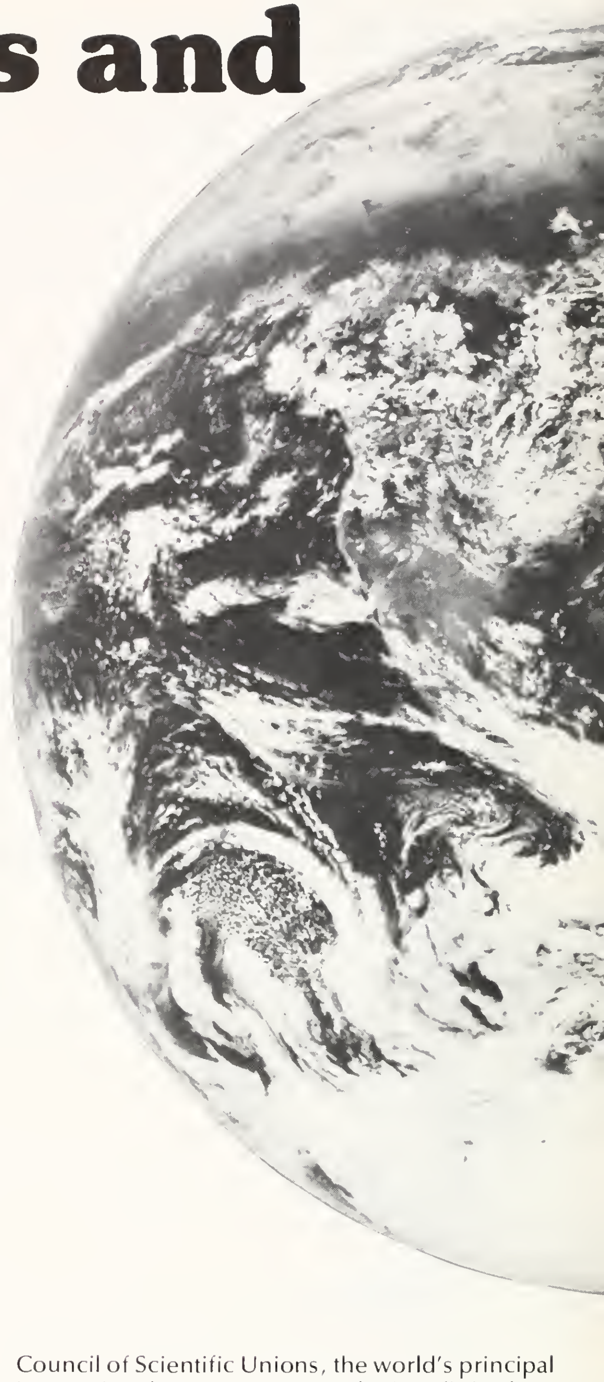
Oceans and

An Introduction

by Robert M. White



It is fitting that an issue of *Oceanus* be devoted to the symbiotic relationship between the oceans and climate. The interlinkages of the oceans, atmosphere, and climate are more than just physical, although the physical linkages between the different parts of the fluid envelope of the planet are fundamental and determinant. The oceans are key to our knowledge of climate past and central to our understanding of climate future.

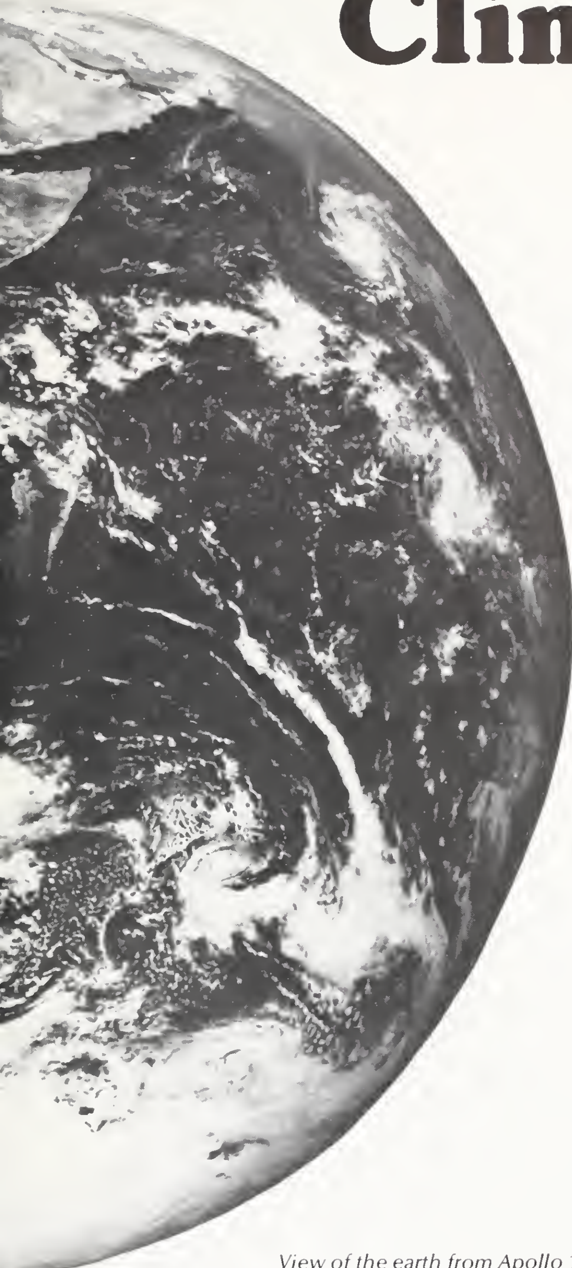
Like the atmosphere, the oceans are an environmental sewer for the wastes of mankind. We now understand that industrial wastes, such as the carbon dioxide released during the burning of fossil fuels, can have consequences for climate that pose a considerable threat to future society. The Geophysics Research Board of the National Research Council in its recent report "Energy and Climate" foresees the possibility of a quadrupling of the CO_2 content of the atmosphere in the next two centuries with a possible increase of 6 degrees Celsius in global surface temperatures. Changes of such magnitude accompany climatic shifts from glacial to interglacial epochs. Whether and to what degree such changes will materialize depends to a large extent on the balance and interchange between the atmospheric and oceanic reservoirs of CO_2.

Experiences of the past decade have demonstrated the consequences of even modest fluctuations in climatic conditions. The drought in the Sahel in the late 1960s and early 1970s, the failure of the Peruvian anchovy harvest and the drought-impacted Soviet grain harvest in the early 1970s, and finally the drought and abnormally cold winters in the United States during the last several years have lent a new urgency to the study of climate.

One result has been the decision by the Federal government to implement a National Climate Program. The 95th Congress enacted the National Climate Program Act (PL 95-367) in 1978. This was a far-reaching action by Congress, establishing a statutory base for a more vigorous and extensive National Climate Program that will focus on the need to improve our understanding of climate and climatic services. President Carter has given his strong support to this national climate effort.

At the international level, the World Meteorological Organization, a specialized agency of the United Nations, and the International Council of Scientific Unions, the world's principal international non-governmental scientific body, have joined to plan a World Climate Research Program. As a preliminary step, the World Meteorological Organization is holding a World Climate Conference this February in Geneva. The conference will bring together leading experts on the scientific aspects of climate and on the impacts of climate upon society. One specific task is to determine whether climate problems are sufficiently serious to warrant a United Nations ministerial-level meeting.

Climate:



View of the earth from Apollo 17. (Photo courtesy NASA)

Important climate-related investigations are already underway. The nations of the world are launching a comprehensive and far-reaching research undertaking — the Global Weather Experiment — as part of the Global Atmospheric Research Program of the World Meteorological Organization and the International Council of Scientific Unions. The experiment will see five geostationary satellites launched simultaneously by the United States, Japan, and the European nations. These will be supplemented by two polar-orbiting satellites. A fleet of aircraft will probe the tropical atmosphere and oceans. More than 40 surface vessels will make oceanic and atmospheric observations, and a network of automatic data buoys will be deployed to study the oceans of the Southern Hemisphere.

The experiment started at the end of 1978 and will continue through 1979. It will yield the basic data necessary to determine the feasibility of extending the time range of weather forecasts and those necessary for understanding seasonal and interannual fluctuations of climate. There are other international programs of importance to climate underway; in the Atlantic, the Mid-Ocean Dynamics Experiment (POLYMODE) is being conducted jointly by the United States and the Soviet Union to seek a better understanding of the dynamics of the large-scale eddies of the Gulf Stream; in the Pacific, the North Pacific Experiment (NORPAX) is probing the interaction between large-scale oceanic and atmospheric phenomena. CLIMAP (Climate/Long Range Investigation Mapping and Prediction) and the Ocean Sediment Coring Program, sponsored by the National Science Foundation, have yielded a new understanding of long-term changes in climate. It is principally the analysis of ocean sediments that has brought us nearer verification of long-standing hypotheses on the causes of ice ages. These now appear to be due to the fluctuations in solar radiation brought about by the changes in the orbital characteristics of the earth.

These large field programs will provide the basic data for understanding climate past and hopefully the data that will enable us to understand the prospects for climate future. However, the true key probably lies in our ability to formulate mathematical models that can simulate both the oceanic and atmospheric systems on computers. Such models offer the best hope of simulating the variability of climate due to changes in both oceans and atmosphere that might be caused by natural or human altering of atmospheric and oceanic processes.

It is an exciting time. The scientific problems are formidable; the technological problems, unprecedented; and the potential economic and social impacts, ominous. Science has an enormous challenge. Can it meet it?

Robert M. White is Chairman of the Climate Research Board of the National Research Council, the principal operating agency of the National Academy of Sciences and the National Academy of Engineering.

The Problems

WINTER – *a snowstorm at Stowe, Vermont. (Photo by F. B. Grunzweig, PR)*

SPRING – *a tornado south of Indianapolis, Indiana. (Photo by David Petty, PR)*

# of Climate Research

by Francis P. Bretherton

How often must our primitive ancestors have paused to wonder at the delicate reawakening of the forest each springtime, or to curse the bitter wind of a cold winter? How often must they have searched vainly for food in a landscape desiccated by an unseasonal drought, or have gathered patiently a small reserve "against a rainy day?" Early man was enveloped by natural forces, their vagaries appreciated intuitively and reacted to on the basis of long experience. As civilization developed,

SUMMER – a forest fire north of Fort Yukon, Alaska. (Photo by Laurence Lowry, PR)

FALL – a hurricane moving along the Florida coast. (Photo courtesy NOAA)

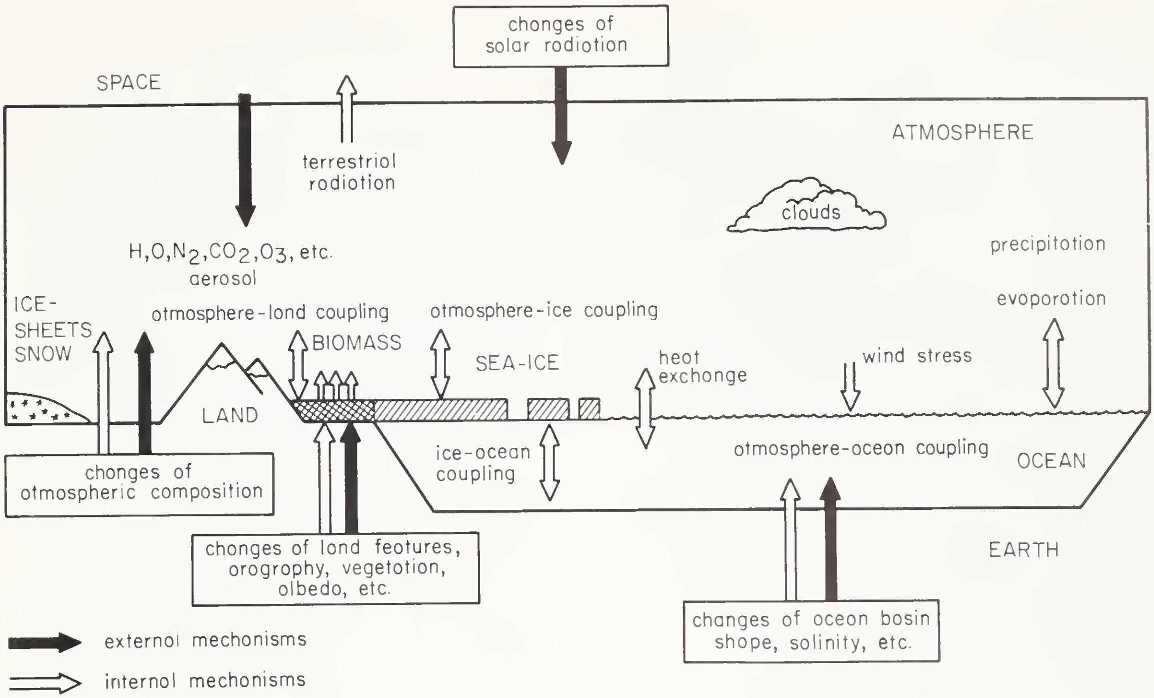
Flooding of the Skagit River near Sedro Woolley, Washington. (Photo by Ron Curbow, PR)

technology was applied to create stability. Settlements were built where the local climate was suitable for growing crops. Houses were constructed to protect the immediate environment against rain, sun, and wind. Later these were heated in winter and air-conditioned in summer. Irrigation systems were devised to mitigate the effects of the dry season. Trade and commerce decreased dependence on local food supplies. Rafts and sailing ships gave way to more reliable transportation. Electronic communications now permit speedy response to natural threats. Life seems isolated from the day-to-day fluctuations in the atmosphere around us. By inhabiting the Antarctic ice cap and exploring the moon, it might appear that man has asserted his independence of climate, and his mastery over the uncertainties of the natural environment.

Yet in some respects the vulnerability of our society to weather and climate variations has actually increased. A feature often found in sophisticated organizations or mechanical systems is a loss of resilience to unforeseen damage or changes in external conditions. Unless adequate precautions are built in, the impact of a single lightning strike on a power distribution network can be devastating. When, under the protection of massive levees, whole cities are built in the flood plain of a notoriously flood-prone river, the effects of occasional extreme high water are magnified, not diminished. One of the great achievements of the last three decades has been the systematic increase of average crop yields in the wheat and corn belts of the United States, achieved by careful selection of varieties and cultivation techniques, and by massive applications of fertilizer. From one point of view, the vulnerability is lessened. Year-to-year variations due to unfavorable weather and climate factors are now only about 15 percent of the total yield, instead of about 50 percent previously. Yet, because of the capital investment required, in that 15 percent lies the difference between a profit and an economic disaster for the farmers concerned. In addition, the world grain market has developed such that a simultaneous drought in India and the Soviet Union has a major impact on business in the United States.

These examples, and public attention, concentrate on the dramatic effects of an extreme event: a local storm, a severe winter, a two-year drought. From a social point of view, climate is just as important as a natural resource, a complex of normal weather that we adjust to and use for our benefit. The dominance of the California fruit and vegetable industry in many parts of the United States is a striking example of how local differences in climate within a region become ingrained in the economic and social fiber of a developed society. Such diversity is a strong positive asset, permitting specialization and optimization to local conditions. Much is known empirically about local climates and how they may be used. Few are wholly good or wholly bad. But in such optimization lie the seeds of vulnerability. Thereafter any departure from normal is likely to be damaging; any rapid change in natural

Harvesting lettuce in the Imperial Valley, California. (Photo by Georg Gerster, PR)



The components of the coupled atmosphere-ocean-ice-earth climatic system. The full arrows (➡) are examples of external mechanisms, and the open arrows (⇒), examples of internal processes in climatic change. (After Living With Climatic Change, *Science Council of Canada)*

or social conditions will upset the balance upon which the whole structure rests. The climate itself is less important than the difference between what it actually is and what it has been perceived or assumed to be. Possibly the most challenging problem of climate research is to clarify the sensitivities of our economy and social system to climate change and to our assumptions about what the climate is. The relevant systems are complex, ill understood, and continuously evolving; the task is daunting in the extreme. Yet as the world struggles to support and feed an ever greater population with ever greater expectations, the margins are becoming tighter and the possibilities for catastrophe are increasing.

But what is climate? The mere definition always provokes a lively discussion at meetings of experts. It seems generally agreed that at a minimum the term includes the local average values of the atmospheric variables that make up weather (temperature, pressure, humidity, windspeed, precipitation, insolation, cloudiness, and so on), together with some measure (variance or probability distribution) of typical fluctuations about that average. Some would include air quality as an important climatic variable. Others would extend the concept to include conditions in the ocean as well as in the atmosphere. However, most confusing is that the period of averaging may vary greatly with the user of the term, indeed even between different contexts for the same user, ranging from a few weeks to many millennia, either sampled at a given time of day or year or averaged over whole days and years. Thus what climate change is to one enthusiast is merely a normal fluctuation within a constant climate to another. Many arguments about whether the climate is getting colder or warmer have occurred not because of doubts over the evidence but because of differing interpretations about what is meant by climate.

The Climate System

An equally important concept is that of the climate system, defined as that complex of physical, chemical, biological and human processes that determine what climate actually is. The boundaries of the climate system are highly elastic, depending on the preoccupations of the speaker and on the time scale of interest. As an example, consider monthly averages. The most relevant part is then the global atmosphere with constant chemical composition (except for varying amounts of water), plus the land surface with the evaporation and storage cycle for moisture, plus the uppermost layers of the ocean and a constant ice cap. It is sometimes helpful to subdivide this system even further by assuming that the ocean surface temperature is given and trying to understand the associated distribution of atmospheric temperature, pressure, and wind. The second stage consists of analyzing the changes in the atmosphere that might arise from certain changes or anomalies in the ocean surface temperature, sea-ice coverage,

or soil moisture distribution. A third stage, usually pursued largely concurrently with the other two, is to consider what processes determine the anomalies.

This approach concentrates on short-term climate fluctuations, with a motivation similar to that of weather prediction. The postulate is that by observing and understanding the current worldwide situation, particularly those anomalies that have a longer response time than most of the atmosphere, a useful forecast can be made of fluctuations in the atmospheric circulation and hence of local climate. If such drivers for the atmospheric system can be identified, it may not be necessary to know in detail how they arise, since the mere observation of an anomaly coupled with experience about its usual persistence could provide very useful information about the future. There have been many research projects aimed at developing such forecasts and much of importance has emerged that should be vigorously pursued. However, there also are some fundamental underlying issues that are unresolved and need attention.

The first question is whether anomalies in ocean surface temperature are on the whole the cause of most changes in the atmospheric circulation or a consequence of such changes. The answer is undoubtedly that both are true, but a quantitative case-by-case assessment is important. If in large measure the ocean fluctuations drive those in the atmosphere, observations of the ocean can provide a useful predictor for the atmosphere. If, on the other hand, the ocean is largely responsive, meteorologists tend to lose interest, though an oceanographer may be properly concerned with the phenomenon.

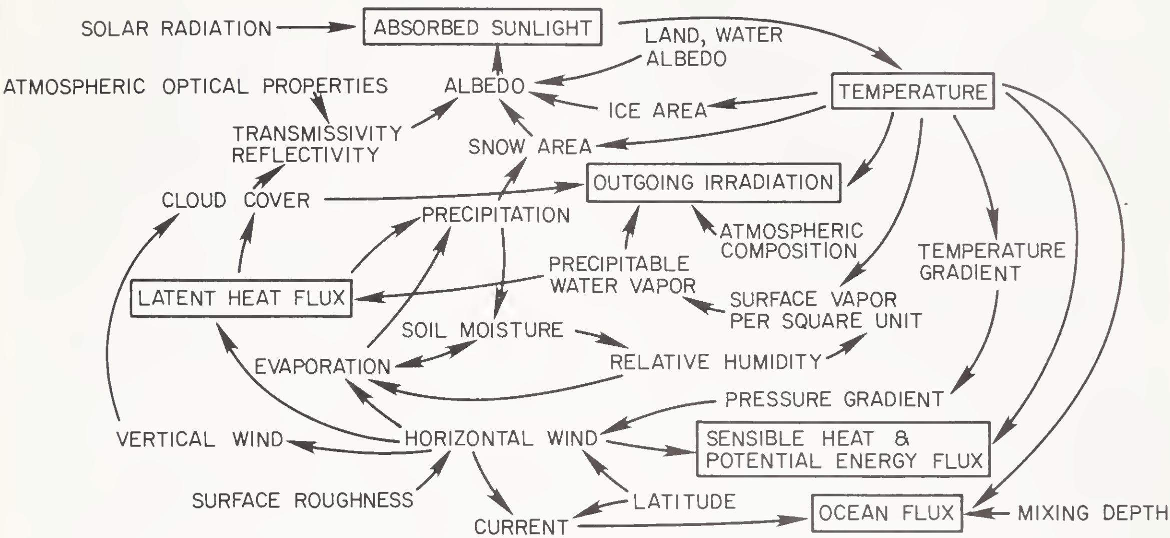
An even more fundamental question concerns the predictability of atmospheric motions a few months ahead. Day-to-day changes in weather are manifestations of large-scale turbulence, a continuously evolving pattern of eddies that is plotted on weather maps as cyclones and anticyclones. The detailed evolution of such eddies from an initial state is determined by the laws of dynamics, but in practice is sensitive to precisely what the initial state is. Two slightly different starting points yield steadily diverging evolutionary paths which, after a few cycles of eddy growth and decay, bear only a qualitative resemblance to each other. Thus, even if we had a numerical model capable of precisely simulating atmospheric dynamics, the duration of useful detailed weather forecasts usually would still be limited by lack of precise knowledge about the current state of the atmosphere to a maximum of one to two weeks. Beyond that time, the model could give a useful description of the average and the statistics of the fluctuations of the weather (climate), but not a meaningful prediction of the individual weather patterns themselves.

Now an assumption underlying the anomaly approach to climate prediction is that changes in the forcing variables (such as sea-surface temperature), which are external to the atmospheric system for the calculations just described, will cause changes in the statistical regime that are large enough to be readily detectable over a month or so above the unpredictable fluctuations associated with weather. When averaged over only one or two months such random fluctuations do not entirely cancel, so the fact that the January average temperature differs from year to year does not necessarily imply a change in statistical regime. Indeed, examination of records in temperate latitudes shows that most, though not all, of the interannual variability can be accounted for in this way, as differing samples of qualitatively the same weather. Only the remaining variability is in principle predictable as a climate fluctuation due to changes in the external forcing.

If this line of reasoning is correct, it leads to a somewhat pessimistic outlook for short-term climate prediction in temperate latitudes, because even if completely successful, such a technique would be unable to explain more than a small fraction of the differences that are most conspicuous to the general public. However, it does not mean that such predictions are worthless. There are occasional circumstances in which the normal progression of cyclones and anticyclones is blocked or diverted for several weeks at a time, for reasons that are presently not well understood. Though rare, these occasions provide the extremes of short-term variations, and simply to be able to identify them in advance would be of enormous value, even if the monthly averages for the remaining time were quite unpredictable. Also, in the tropics the records show large changes in averages of one to five years, far greater than the sampling errors due to day-to-day weather. These variations in the atmosphere are certainly associated with substantial changes in the ocean, though the causal relationship is uncertain. Documenting and understanding these variations in equatorial regions in both media should be a very significant objective for climate research for the next decade.

A quite different perspective on the climate system comes from asking broader questions — why the global climate is as we find it and whether it might have been quite different in past ages. The averaging time is now a century at least and year-to-year differences are mere statistical fluctuations. The effects of interest are large, such as ice ages and desert formation, and are observed not by direct measurement but semiquantitatively through proxy data, such as the ratio of oxygen isotopes in ice cores, or the species of plankton skeletons in sediments. Now one needs to consider

CLIMATIC CAUSE-AND-EFFECT (FEEDBACK) LINKAGES



(Source: Schneider, 1976)

the circulation of the whole ocean, not just the surface layers, and one must model the formation and decay of ice sheets, even the changing pattern of land and water as continents drift. It is obvious that, in an overall sense, the temperature of the earth is determined by radiative equilibrium in space, dominated by the luminosity of the sun and our distance from it, but major variables in that balance are the reflection of sunlight from clouds and snow, as well as the atmospheric transparency to infrared radiation. Also the temperature contrasts over the surface of the earth are greatly modified by the poleward transport of heat in the ocean. A key question for ocean climate research is how to measure the net heat flux carried by subtropical gyres in different oceans and by the slow formation of deep water in subpolar regions. Recent evidence that 50 million years ago the bottom water in the North Pacific was 10 degrees Celsius warmer than now raises fascinating issues of great significance. Does it mean that the atmosphere in polar regions was also 10 degrees Celsius warmer, or that access to polar regions was blocked by continental drift? Another question of importance is just how do the subtle variations in the shape of the earth's orbit around the sun, which were highlighted by Milankovitch, become translated into substantial changes in ocean temperature and what do they imply for climate on land?

The Carbon Dioxide Question

An even broader point of view notes that the atmospheres of Mars and Venus contain large fractions of carbon dioxide, as did that of earth in pre-Cambrian days. Carbon dioxide, like water vapor, is relatively transparent to incoming visible solar radiation, but opaque to the infrared radiation emitted by bodies at the temperature of the planets. This leads to the greenhouse effect, in which the surface of the planet is warmer than simple black-body radiative equilibrium would indicate. Relative to earth, on Venus the atmosphere is thick, and because of poleward heat transports the surface temperature is almost uniform and, thanks to the greenhouse effect, very hot (800 degrees Celsius). On Mars the atmosphere is thin and dry, and plays only a minor role in moderating the radiative equilibrium temperature, except in polar regions where solid carbon dioxide condenses like snow. There is nonetheless evidence that in some past era the Martian climate must have been quite different, with liquid water actively shaping the land surface. The history of earth has been a middle course. A little warmer and the oceans would have boiled, the water vapor forming an irrevocable greenhouse. A little cooler and they would have frozen, reflecting enough sunlight to keep the planet eternally cold. According to accepted theories of stellar evolution, when the earth was formed some 4½ billion years ago, the luminosity of the sun was only half its present value, whereas the mean distance from the sun was much the same as now. Why did the oceans not freeze over, which according to the present basis for equilibrium should assuredly have happened? The answer is of course speculation, but to find it we have to look back at conditions before that great transformation some 1½ billion years ago when somewhere in the ocean there evolved forms of life that liberated molecular oxygen as a by-product of photosynthesis. Then, it is believed, the atmosphere was a reducing one, almost totally

Drought in Upper Volta, one of six countries in the Sahelian zone along the southern edge of the Sahara. Carcasses of animals lie around a camp of Mali nomads at Christine Wells, where the tribesmen came in search of food and water. (Photo by F. Botta, FAO)

lacking in oxygen, but rich in ammonia and carbon dioxide. We do not know how thick it was, but it must have been dense enough for the greenhouse effect to prevent the oceans from freezing (otherwise the evolution of life could not have occurred) yet not so dense that the oceans boiled. In any case, the climate could not have been the same as now, but had it been a little different from what it was, we would not be here to wonder why.

This humbling perspective underlies the greatest preoccupation of all in climate research. How fragile is our climate, and is it possible that mankind with modern technology and economic systems is progressively destroying its very basis? We are all familiar with the local air pollution in cities and industrial areas. Less well known is the acid rain that increasingly falls thousands of kilometers downwind, corroding automobiles, stunting vegetation, and leaving lakes and streams devoid of fish. Fortunately, the lifetime of oxides of nitrogen and sulphur derivatives in the lower atmosphere (before they are scavenged by precipitation) is only a few days, so such problems are regional rather than global, and, though severe, can in principle be cured fairly quickly once corrective action is taken. More subtle dangers arise from man-made chemicals, which are very stable and have no natural sources or sinks. Eventually they diffuse everywhere. For example, even though present at concentrations of only parts per billion, photo-decomposition of fluorocarbons in the upper atmosphere has been shown to liberate atomic chlorine, catalyzing a reduction in the natural ozone that shields the earth's surface from harmful ultraviolet radiation. Here the time lag between release into the atmosphere and its consequences is some 10 to 20 years, and anticipation is vital.

In this case, the economic consequences of controlling production and regulating disposal are relatively minor, and it seems that government actions will avert serious danger, but the experience has demonstrated clearly how inadequate our knowledge is of how trace chemicals — such as sulphur, active nitrogen, and carbon derivatives — circulate in our natural environment, of how they are transferred from land to ocean to atmosphere. What are the major sources and sinks, natural as well as man-made? These biogeochemical cycles touch many disciplines, are uncertain in major respects, and are potentially very important in subtle and ill-understood ways. A strategy of exploratory research is required, patiently unravelling the major pathways, particularly across disciplinary boundaries — always prepared for the unexpected.

Probably of highest priority is the carbon cycle. Thanks to careful measurements by a few farsighted individuals, we know that the concentration of carbon dioxide in the atmosphere has been increasing steadily, for the past two decades at least, at a rate commensurate with, but not equal to, the release from the burning of fossil fuels such as coal and oil in industrialized countries.

Farmstead in dust bowl area of northwest Texas, April 1938. (Photo courtesy USDA – Soil Conservation Service)

The effects on climate of such an increase, if it continues, are not precisely known, but in general are expected to be a global warming rising above the noise level of interannual variability within a century. Though this may seem a long lead time, the time scale for remedial action or, as seems more likely, adjustment to the consequences, is also large. Key research questions are to account for the disposition of the half of the carbon dioxide already released that has not so far appeared in the atmosphere, and to estimate the effects of the oceans in moderating regionally the temperature changes to be expected as the atmospheric concentration increases. Both these questions require greatly increased understanding of the general circulation of the oceans, both by tracer techniques to follow the vertical mixing of surface water down into and below the thermocline, and by modeling calibrated with field measurements to dynamically simulate the changes in surface temperature and poleward heat transport associated with changing wind fields and radiative balances. This is fundamentally a long-term program with few shortcuts, requiring above all skillful integration of knowledge from many areas of physical and chemical oceanography, with the perspectives provided by sediment cores and plate tectonics as essential background from past eras.

A Look to the Future

It will be apparent from this article that climate research is a vast topic, requiring insights ranging from precise but crucial details to sweeping qualitative generalizations. It involves, and could arguably be said to encompass, many disciplines, from meteorology and oceanography through glaciology, geochemistry, and the evolution of life to economic geography, geopolitics, and systems analysis. Most important, however, is an attitude of mind, that of the expert who absolutely knows his own specialty and patiently strives to make progress with it, yet who at the same time can rise above the details and frustrating pockets of uncertainty to join with colleagues of quite different background to piece together the essentials of the overall picture, sketching where appropriate, meticulous if necessary, but never abandoning the vision of the grand design. It is far easier to describe the problems than it is to answer them, and there will be much self-doubt and skepticism. Progress will be fitful and will come in unexpected ways. Only our children will know if it was adequate.

Francis P. Bretherton is President of the University Corporation for Atmospheric Research, and Director of the National Center for Atmospheric Research, Boulder, Colorado.

The National Center for Atmospheric Research is sponsored by the National Science Foundation.


DANGER

Carbon Dioxide and Climate

by Peter G. Brewer

The air we breathe is not identical to that which sustained our forefathers. We are now used to hearing about all the airborne ills of the 20th century — urban smog, pesticides, radioactive debris, to name just a few. However, there is one unseen artifact of man's activities that may have the greatest impact of all. It is carbon dioxide (CO_2), familiar as the respiratory product of our lungs and as the sparkle in a glass of champagne.

The amount of carbon dioxide in the atmosphere is increasing. We do not know exactly what the concentration was before the industrial revolution, but responsible estimates place the figures at approximately 0.000270 to 0.000290 atmospheres total pressure of CO_2, of 270 to 290 parts per million (ppm). The concentration at this time is approximately 330 ppm. The phenomenon of increasing CO_2 in the atmosphere was first reported in 1938 by G. S. Callendar, a British engineer. He noted that: "Few of those familiar with the natural heat exchanges of the atmosphere, which go into the making of our climates and weather, would be prepared to admit that the activities of man could have any influence upon phenomena of so vast a scale." Nonetheless, Callendar demonstrated that man had added about 150 billion tons of CO_2 to the air through the burning of fossil fuels in the 50 years preceding 1936, and that this had the potential to alter climate. Callendar's original calculation is shown in Figure 1. Current rates of fuel consumption make this amount seem small. We now add approximately 18 billion tons of CO_2 *per year* to the atmosphere from fossil fuel consumption. This amount is not large compared to the vast natural fluxes of CO_2 within forests and oceans, but the essential point is that the natural fluxes were in a carefully balanced steady state before the advent of industrialization. It is the new input of very old carbon that concerns us here.

Of all the CO_2 that has been added to the atmosphere, only about 50 percent currently remains there. The fate of the missing 50 percent is still a matter of active debate, but the great bulk of it must have gone into the oceans. The atmospheric CO_2 that remains has the capacity to alter climate. This arises from selective absorption of the sun's radiation by the CO_2 molecule. Incoming radiation from the sun, predominantly of higher energy and shorter wavelength (around 1 micron), is transmitted to the earth's surface through the atmosphere. The carbon dioxide molecule is transparent to radiation of these wavelengths. Back radiation of heat from the earth's surface to space takes place at longer wavelengths, around 10 microns, and both CO_2 gas and water vapor have absorption bands at these wavelengths. This longer wavelength absorption traps the back radiated heat, and thus, as any mountain climber knows, our atmosphere is heated from below. The effect of adding CO_2 to our atmosphere is to create a warmer world (often called the greenhouse effect). Yet how much warmer, and how soon, and for how long? How fast will we add CO_2 to the atmosphere, compared to the rate at which the ocean will remove it, and what will happen to seawater itself? Will all areas of the globe equally bear the brunt of the projected climate change, and what are the social and economic consequences? These questions are presently exercising the very best minds and will continue to do so for many years to come.

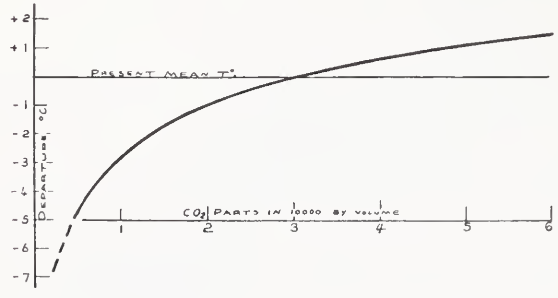


Figure 1. G. S. Callendar's calculation of 1938, appearing in the Quarterly Journal of the Royal Meteorological Society. *It shows the relation between atmospheric carbon dioxide and surface temperature in the temperate air region. Recent, more sophisticated, calculations do not change this result greatly.*

Coke plant on the Monogahela River at Pittsburgh, 1973. (Photo John Alexandrowicz, EPA-DOCUMERICA. Courtesy U.S. Environmental Protection Agency)

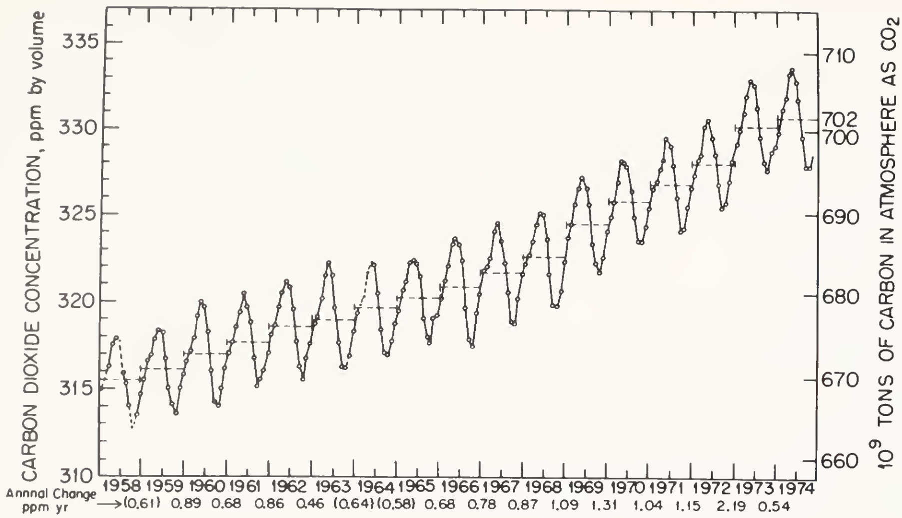


Figure 2. Time record of atmospheric CO_2 concentration from 1958 to 1974, as recorded at the Mauna Loa observatory, Hawaii, by C. D. Keeling and co-workers. (Source: Baes, et al., 1976. The Global Carbon Dioxide Problem, Oak Ridge National Laboratory, Report No. ORNL-5194)

Carbon Dioxide in the Atmosphere

The first step in beginning to answer these questions is to understand the carbon dioxide distribution in the atmosphere. Although the paper by Callendar in 1938 attracted worldwide attention, it was not until the 1950s that a long-term, high-precision monitoring study of atmospheric CO_2 was undertaken. The exemplary work of C. D. Keeling and colleagues at Scripps Institution of Oceanography in establishing a monitoring station at Mauna Loa, Hawaii, has provided us with an excellent record from 1958 to the present (Figure 2). Two effects can be clearly seen. First, there is an annual sinusoidal ripple, of about 4 to 6 ppm amplitude. This seasonal cycle is driven by the stripping of CO_2 from the atmosphere in the northern summer by the green plants in forests and grasslands, and replenishment of CO_2 by decomposition and respiration during the northern winter. At Point Barrow, Alaska, this annual variation is as much as 15 ppm, whereas at the South Pole it is as little as 2 ppm. Second, a steady increase of the mean signal with time is superimposed upon these annual fluctuations. The mean rate of increase from 1958 to the present has been about 0.8 ppm per year, and is currently close to 1 ppm per year.

It is too easy to say that this increase is due to the burning of fossil fuels. Since only half of the CO_2 injected into the atmosphere currently resides there, the rate of increase depends upon the balance of the rate of production versus the rate of loss by dissolution of CO_2 gas (forming bicarbonate [HCO_3^-] ions) in the ocean. Moreover, the burning of fossil fuels, although the major source of CO_2, is by no means the only one. Cement production, which may be regarded as removal of CO_2 from limestone, adds about 2 percent to the anthropogenic CO_2 flux. Recently George M. Woodwell at the Marine Biological Laboratory in Woods Hole, Massachusetts, and co-workers have pointed out the importance of large-scale changes in terrestrial vegetation. Reduction in the terrestrial biomass due to harvesting forests, burning firewood, and other massive agricultural practices can certainly perturb atmospheric CO_2 fluxes. But it should be noted that man cannot continue to burn forests forever, and in the long run these sources are small compared to fossil fuels — the vast reserves of which are estimated as being about $7{,}400 \times 10^9$ tons of carbon. These reserves are approximately four times larger than the estimates of biotic reserves.

The residence time of the average CO_2 molecule in the atmosphere is about 10 years, after which time it is likely to be incorporated into one of the more stable carbon reservoirs, such as the deep ocean. The size of the atmospheric CO_2 reservoir is quite small, on the order of 7×10^{11} tons of carbon, and especially when compared to the huge oceanic reservoir, which contains approximately 390×10^{11} tons of dissolved carbon as CO_2 in its various chemical forms. We should note that the 10-year atmospheric residence time of the average CO_2 molecule is *not* identical to the decay time of the transient CO_2 pulse currently being introduced. We are not sure what this time would be. A direct experiment — shutting down our factories, mines, wells, and automobiles — is, of course, impossible. One model calculation by U. Siegenthaler and H. Oeschger of Bern, Switzerland, suggests that if *all* fossil fuel reserves were burned, then the atmospheric CO_2 fraction could be 80 percent of that produced by combustion. This level would drop very slowly to some new equilibrium state that would still represent a significantly higher atmospheric CO_2 level than existed before the industrial revolution.

The extrapolation of the observed atmospheric CO_2 curve to predict future atmospheric CO_2 levels is not simply a matter of determining a mathematical formula. It requires a prediction of future fossil fuel combustion

practices, not nationally but globally, and by societies whose attitude toward environmental concerns may be legitimately different from those in the United States. It also requires the ability to recognize the effect of shorter-term terrestrial biomass changes. And perhaps more importantly, it requires a knowledge of whether the ocean will continue to absorb CO_2 at approximately the same rate as it does today.

Carbon Dioxide in the Oceans

The chemistry of carbon dioxide in seawater is complex. In its hydrated form as carbonic acid (H_2CO_3) it can dissociate to form bicarbonate (HCO_3^-) and carbonate ($CO_3^=$) ions. Carbon dioxide added to seawater will react with carbonate ions as in $CO_2 + CO_3^= + H_2O \rightleftharpoons 2HCO_3^-$, and the removal of carbonate ions will eventually permit more calcium carbonate from the sediments to dissolve. The dissolution of CO_2 gas is controlled by its partial pressure (pCO_2) in seawater. The first measurements of the oceanic pCO_2 were made in the early part of this century by shaking a seawater sample in a closed jar to equilibrate it with the contained atmosphere. Modern techniques equilibrate seawater with air by means of a showerhead, or a paddle wheel device, and measure the CO_2 content of this air with an infrared analyzer. By continuously pumping water from a moving ship and automating the analytical measurement, it is possible to obtain a detailed record of the pCO_2 over vast areas of the ocean (Figure 3). The contours on the map in Figure 3 indicate departures from equilibrium with the atmosphere, in units of ppm. High values, such as those in the equatorial Pacific, represent regions where the ocean is outgassing CO_2 to the atmosphere. This results from upwelled, cooler water (bearing an excess of CO_2) being warmed at the surface. Since gases are less soluble in warm water than in cold, the tendency is to put CO_2 into the atmosphere. Low values, such as those in the Atlantic north of 50 degrees North, represent sinks for atmospheric CO_2. Surface water, in equilibrium with the atmosphere at lower latitudes, moves northward, cooling more rapidly than it can dissolve atmospheric CO_2. The net result is to create a greater than 100 ppm disequilibrium between the atmosphere and the sea, resulting in a sink for atmospheric CO_2. The Figure 3 map represents the normal oceanic steady state — the one that has held our atmospheric CO_2 level constant for many thousands of years.

We are currently changing this situation, but it is not clear how. Simple calculations, based on downward vertical diffusion, suggest that the height of the seawater column which has effectively "seen" the anthropogenic CO_2 increase is about 700 meters. A box model calculation of this kind is well suited to the prediction of future atmospheric CO_2 levels, but unsuitable for guiding an experimental program designed to measure these changes. For instance, it is clear that CO_2 is not penetrating downward in the equatorial Pacific; this, however, is compensated for by extraordinary penetration in the important areas of bottom water formation, such as the Norwegian and Weddell seas. Moreover a map of pCO_2 distribution tells us nothing of the

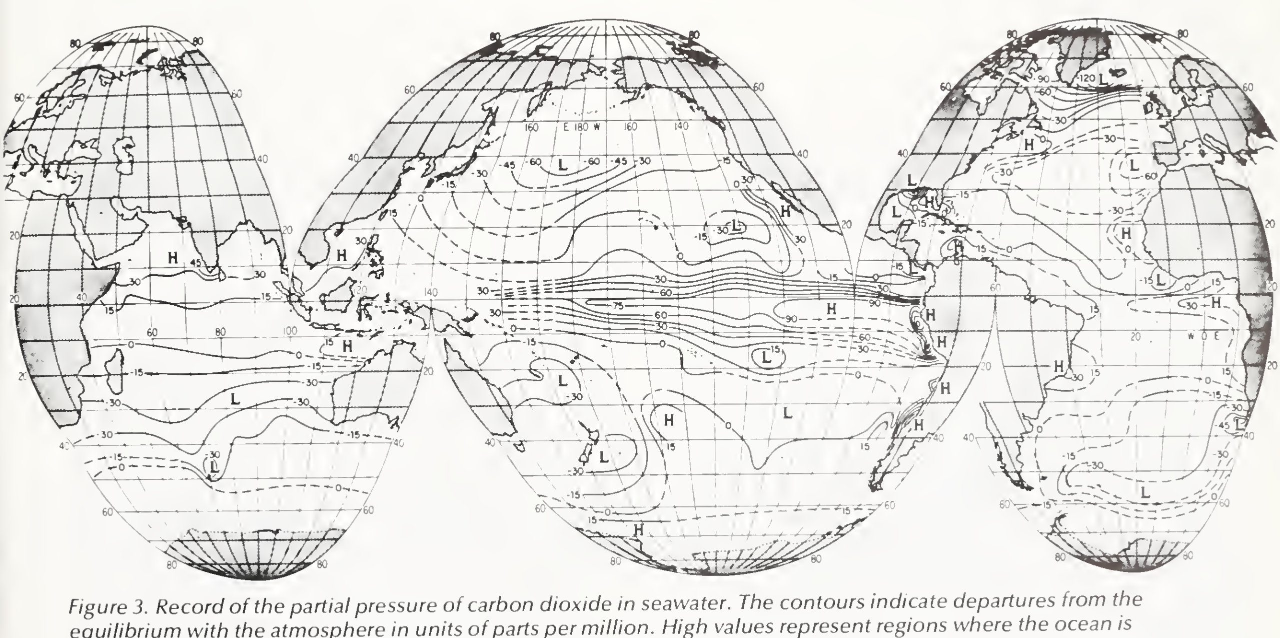


Figure 3. Record of the partial pressure of carbon dioxide in seawater. The contours indicate departures from the equilibrium with the atmosphere in units of parts per million. High values represent regions where the ocean is outgassing CO_2 to the atmosphere. Low values represent sinks for atmospheric CO_2. (After C. D. Keeling, 1968)

gas exchange rate. We know from the efforts of W. S. Broecker and T. Takahashi of the Lamont-Doherty Geological Observatory during the GEOSECS program (see *Oceanus* Vol. 20, No. 3) that the mean CO_2 exchange rate, as estimated from the distribution of radioisotopes such as carbon-14 and radon-222, is about 20 moles per square meter per year (880 grams $CO_2/m^2/yr$).

The vertical distribution of CO_2 in the ocean shows considerable variability. Ordinary surface seawater contains about 2 millimeters of CO_2 per liter (.088 grams CO_2 per liter). However, surface waters constitute only about 10 percent of the oceanic volume. The remaining 90 percent of deep ocean water contains about 15 percent more CO_2. This increase is due to biological activity. Green plants growing at the surface fix CO_2 as organic carbon (and as calcium carbonate), and when they die and sink return this CO_2 to deep waters. It is vital to understand this cycle in any attack on the CO_2 problem; however, unless the anthropogenic CO_2 is in some way fertilizing the ocean (and this is unlikely), then this biological flux cannot respond in any direct way to the atmospheric CO_2 increase.

Although the atmospheric CO_2 increase can be measured directly, the oceanic CO_2 increase is not as easily detectable. The current limit of precision of total oceanic CO_2 measurement is approximately $\pm$ 10 micromoles per kilogram. Current work at the Woods Hole Oceanographic Institution is leading to an increase in precision, and a goal of $\pm$ 1 micromole per kilogram may be attainable. Due to the complex chemistry of CO_2, we must consider the buffer factor, or Revelle factor as it is frequently called, in seawater. This is given by the relationship

$$\mathbf{R} = \frac{\Delta\, pCO_2/pCO_2}{\Delta \sum CO_2/\sum CO_2}$$

and in surface ocean water it has a value of about 10. Thus an increase in oceanic pCO_2 of about 50 ppm (corresponding to the atmospheric increase) has probably led to a total increase of 25 to 30 micromoles of carbon dioxide per kilogram on the ocean surface. This is currently at the very limit of detection.

By far the greatest contribution to our knowledge of CO_2 uptake by the ocean has come from radiocarbon measurements, particularly bomb radiocarbon from the nuclear weapons tests of the early 1960s. The correspondence between bomb radiocarbon and anthropogenic CO_2 is not perfect, because in addition to the different time scales of introduction (the source function), we must consider the difference in time of equilibration. It has been shown that the time constant for the achievement of chemical equilibrium is 10 times faster than for the achievement of isotopic equilibrium. As time increases and the CO_2 signal becomes larger, direct observation becomes more important in understanding the chemical consequences. The question of whether significant dissolution of calcium carbonate ($CaCO_3$) in marine sediments will take place is crucial. The surface ocean is supersaturated with respect to the two mineral forms of $CaCO_3$, calcite and aragonite. However, the deep sea is undersaturated with these minerals due to temperature, acidity (pH), and pressure effects, with dissolution of these components of the sediments occurring. The adding of CO_2 to the ocean lowers pH and causes increased dissolution of $CaCO_3$. This effect will ultimately enhance the capacity of the oceans to absorb CO_2, but penetration of CO_2 into the deep ocean is not yet sufficient to create any detectable change, nor will this be likely to occur for several decades. Predicting the likely consequences of such a change, however, is not easy.

Predictions of Climate Change

Although a scientist can be on safe ground in discussing the observed trends in atmospheric and oceanic CO_2, the prediction of climate change and its likely effects is fraught with peril. Current articles on this topic can confuse even the most experienced observer.

Most articles on climatic effects conclude that if the atmospheric CO_2 content was doubled (to around 600 ppm), we would experience a noticeable change in global climate patterns. We are likely to reach this point around the end of the next century, though scarcity and responsible action might delay this. S. Schneider of the National Center for Atmospheric Research has reviewed the various CO_2 climate models, concluding that the global surface temperature increase resulting from a doubling of the atmospheric CO_2 content is likely to be between 1.5 and 3 degrees Celsius, with the greatest change occurring in the polar regions. This estimate is similar to that of S. Manabe and R. T. Wetherald of the Geophysical Fluid Dynamics Laboratory of the National Oceanic and Atmospheric Administration at Princeton, New Jersey, but it is thought that this may be too high or too low due to the inadequacy of even the most sophisticated climate models.
warming could occur by the year 2000. From his examinations of natural climate cycles (recorded in the oxygen isotopic record of the ice at Camp Century, Greenland), he concludes that the period since 1940 has been part of a natural cooling cycle, partially offset by the CO_2 effect. The last decade of this century could see the onset of a natural warming trend, augmented by CO_2 warming. J. H. Mercer of Ohio State University has recently postulated the "threat of disaster" through melting

of the West Antarctic ice sheet in the next 50 to 200 years. He points out that this could lead to a 5-meter rise in sea level and consequent flooding of low-lying areas, such as Florida and the Netherlands. D. M. McLean of Virginia Polytechnic Institute has speculated that similar abrupt climatic warmings in the past, such as those occurring in the late Mesozoic era, were responsible for worldwide faunal extinctions. He suggests that a warming today could result in similar massive extinctions of animal life, comparable to the end of a geologic era.

The alternative view — the economic consequences of preventing such change — has been examined by Siegenthaler and Oeschger. They have calculated the rate at which we could burn fossil fuel if we were to hold the atmospheric CO_2 level below some critical point, say a 50 percent increase. The results indicate that a continuation of the present trend — a 4 percent increase in the rate of CO_2 production each year — can continue only until the turn of the century. A significant decline in CO_2 production, and probably use of alternative energy sources, would then be required. The limiting factor is the rate of CO_2 uptake by the ocean.

Most scientists today would agree that very significant change in the world is possible, but none can state with absolute authority what the change will be. The effect of climate change on crop production is a vital statistic. Warmer climates could increase the northern limit of cultivation, but the effect on rainfall pattern is uncertain. Few people today would be as sanguine as Callendar, who in 1938 cheerfully remarked that the increase in carbon dioxide in the atmosphere "is likely to prove beneficial to mankind in several ways."

Peter G. Brewer is a Senior Scientist in the Chemistry Department at the Woods Hole Oceanographic Institution.

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Announcement

The Third International Congress on the History of Oceanography will be held at Woods Hole, Massachusetts, September 22-26, 1980. As part of the celebration of the 50th anniversary of the Woods Hole Oceanographic Institution, the Congress will be followed the next week (Sept. 29-Oct. 4) by an assembly on current and future oceanography.

The Congress has the approval of both the International Union of History and Philosophy of Science and the Centre International d'Histoire de l'Océanographie.

Expressions of interest in this Congress, particularly from those who plan to contribute papers on any aspect of the History of Oceanography, will be most welcome as soon as possible. Daniel Merriman, Professor Emeritus of Biology, Yale University, is Chairman. Contact him at 298 Sperry Road, Bethany, Connecticut 06525.

The Ocean Heat Balance

by Kirk Bryan

The heat balance of the ocean concerns the study of the income and outgo of heat energy at the surface. Using accounting principles, oceanographers and meteorologists try to quantify the large-scale exchange of heat energy between the oceans and the atmosphere. The term heat balance suggests that the income and outgo of energy should be exactly equal over some period of time — a calendar year, for example. But since climate changes exist on various time scales, a true balance seldom exists. Surpluses and deficits persist for long periods, but are difficult to detect with existing measurements. Heat balance, therefore, is one way of looking at the fundamentals of the role of the ocean in climate.

It is generally thought that "the Gulf Stream warms Europe," or that "the Peru Current cools the west coast of South America." Such statements are not specific — where does one begin to gather evidence to prove or disprove them? One way to learn something about the workings of a large organization is to start with a perusal of its financial budget. Similarly, studying the annual heat budget of the ocean helps us learn about the large-scale interaction of the atmosphere and ocean. In both cases, the budget numbers alone give little insight. What budgets provide are clues and guidelines that must be followed up by further fact-finding.

Data on the temperature structure of the upper oceans are rapidly building up in repositories, such as the one organized by Fritz Fuglister at the Woods Hole Oceanographic Institution, or the much larger one at the World Oceanographic Data Center in Washington, D.C. These data have been largely collected by bathythermographs, instruments used to obtain temperature depth profiles from a ship underway. Profiles of the upper ocean are obtained from research vessels, merchant "ships of opportunity," and aircraft.

Another impetus for studying ocean heat balance is the availability of new measurements from satellites. Radiation measurements made from space are providing the global external energy inputs and losses. Estimates from satellites of cloudiness, sea-surface temperature, and wind may soon be precise enough to calculate the internal heat exchange between ocean and atmosphere on a day-to-day basis.

(Photo by Jim Broda)

Solar collector panel for heating water, mounted on top of adobe house at Corrales, New Mexico. (Photo by Tom McHugh, PR)

The Tropical Ocean: A Solar Collector

Today an array of rooftop solar collectors excites nearly the same envy as a late model car. Yet the remarkable solar heating system of our planet is taken for granted. The planetary heating system combines the advantages of active and passive elements. Although it uses both heated air and water, it is the water portion that interests oceanographers — the role of the oceans in the global heat balance.

The efficiency of a solar collector can be defined as the ratio of the amount of heat collected relative to the incident solar energy. The efficiency of a rooftop collector may vary from 50 to 80 percent or greater, depending on design and quality of materials used. The tropical oceans of the world act as a giant solar collector. The clear water often found in the tropics is ideal for the deep penetration of visible light and the short-wave radiation from the sun, which has an extremely high surface temperature. On the other hand, the long-wave, back radiation from the ocean at ordinary temperatures cannot penetrate more than a few millimeters into the surrounding water.

Direct solar radiation deposits energy in the water below the surface that must eventually be carried away to other parts of the ocean, or transferred back to the surface by conduction and turbulence. The processes that can cause heat losses at the surface are shown in Figure 1. Long-wave radiation from a thin film of surface water can directly transfer energy from the ocean to

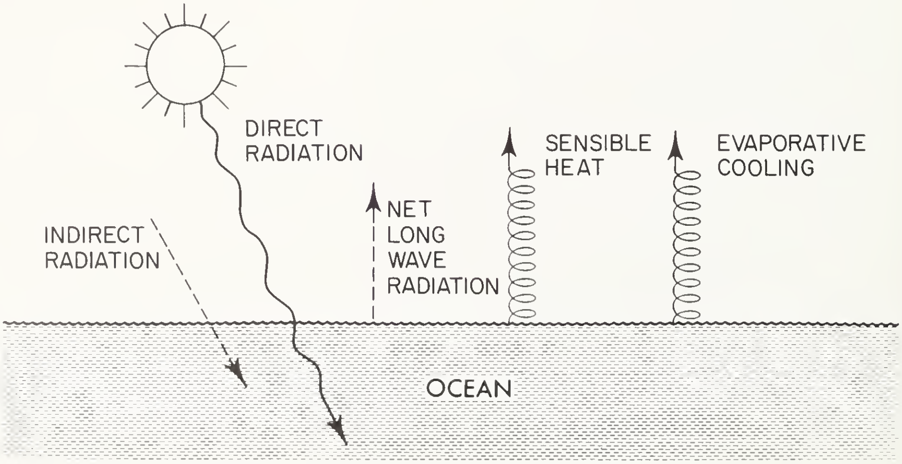

Figure 1. Five principal elements of the surface heat balance.

Figure 2. Observed surface temperature of the oceans averaged over all seasons.

the upper atmosphere or space. Sensible heat* is transferred directly from water to the air above by turbulence. Evaporation also cools the water surface. Surprisingly, the wavy surface of the ocean increases its collector efficiency, since at low solar angles a broken surface has a lower reflectivity than a flat sea. Sensible heat transfer at the sea surface depends on the temperature difference between the water and the overlying air. Since the air/sea temperature difference is generally small in the tropics, the dominant cooling mechanism is evaporation. The amount of water vapor that air in contact with the sea surface can hold increases at an accelerated rate with increasing sea-surface temperature. At normal wind speeds, and normal relative humidities in tropical ocean areas, evaporative cooling starts to exceed solar heat input at about 28 to 30 degrees Celsius. As the sea-surface temperature starts to exceed the critical value of 28 to 30 degrees Celsius, evaporative cooling exceeds the energy supplied by the sun, and the sea-surface temperature falls. The control exerted by evaporative cooling is an illustration of what engineers call negative feedback. It helps to explain why sea-surface temperatures are quite uniform over a broad area in the tropics (Figure 2).

The efficiency of the tropical oceans as a solar collector is naturally highest where surface temperature, and therefore evaporative cooling, is lowest. Low temperatures also suppress trade wind cumulus clouds, which allow more solar radiation at the ocean surface. Figure 2 shows that the lowest surface temperatures in the tropics lie along the west coast of Africa, off the Horn of Africa, and off Peru. There also is a low temperature band along the equator in the eastern Pacific. These are all areas of maximum upwelling of deep water. Nutrients brought up from below allow these areas to have abundant biological productivity. The heat balance maps of these areas by two Woods Hole scientists, A. F. Bunker and L. V. Worthington (1976), suggest that the ratio of heat taken up by the ocean to incoming solar energy, or collector efficiency, is 30 percent, or better. Over most of the tropics evaporative losses are more prevalent and the collector efficiency is only 20 percent, or less. Naturally, the collector efficiency of the tropical ocean could be improved by covering the entire region with a glass plate. However, this should not be done without a careful, Environmental Impact Study!

*Heat resulting in a temperature change but not a change in state.

Mid-Latitudes: A Solar Collector/Storage Unit

While the tropics receive a nearly steady energy supply throughout the year, mid-latitude oceans receive a surplus of energy in summer and a deficit in winter, with little net gain or loss on a yearly basis (Figure 3). Since cooling at the surface balances the solar energy received, the collector efficiency for an entire year would be zero in this area. However, from April through September, a large surplus of solar energy is received in mid-latitudes. During this period, the mid-latitude oceans are a highly efficient solar collector. The excess energy is stored in the summer thermocline, which forms in the upper 100 meters of the water column. The exact amount of heat stored in summer varies

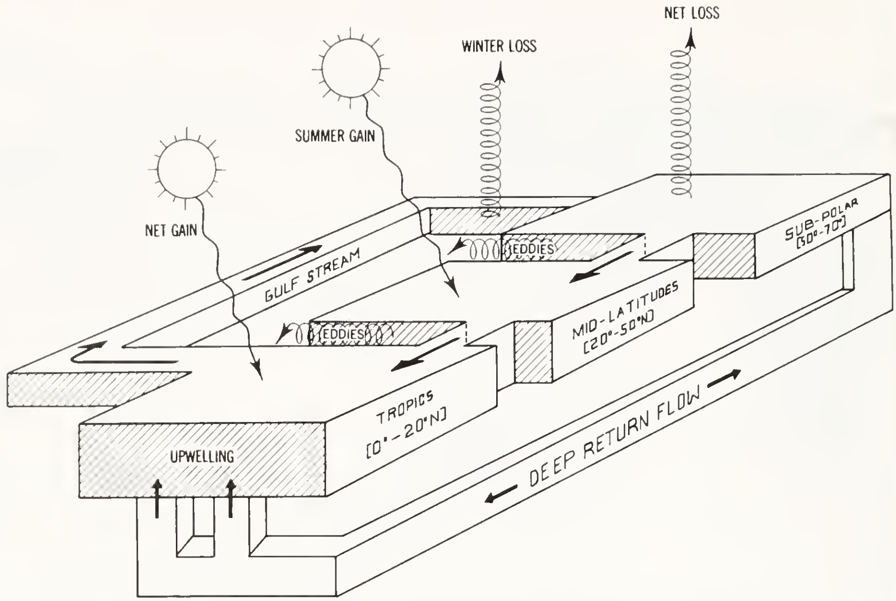

Figure 3. The main avenues of heat exchange in the North Atlantic.

considerably from year to year. Since it involves only local processes, heat storage by the ocean is analogous to a passive solar heating system. On the other hand, the mid-latitudes also are an active element in the planetary heating system, because they are situated between the tropical oceans, which receive a net surplus of energy on an annual basis, and the sub-Arctic and Arctic oceans, which sustain a net loss over the same period. Mid-latitude oceans act as a passageway for the poleward transfer of heat from the tropics to high latitudes, a function required for a long-term balance.

Existing data suggest that several mechanisms are responsible for the large-scale poleward flux of heat by ocean currents. A popular idea is that the Gulf Stream carries warm water northward, which is compensated for by the southward transport of colder water on the eastern side of the ocean. Another mechanism involves the fact that part of the surface water flowing poleward in the North Atlantic cools and sinks at higher latitudes. If this water returns to the south at lower levels, the net overturning motion transfers heat poleward. In the atmosphere, transient cyclones are the dominant transporting mechanism of heat energy. The ocean equivalent of atmospheric cyclones are the energetic meanders of the Gulf Stream and related features studied by the recent Joint U.S.-U.S.S.R. Mid-Ocean Dynamics Experiment (POLYMODE) and MODE programs, and their ancestors, Gulf Stream '50 and '60 (see *Oceanus,* Spring 1976). From simple order of magnitude estimates, it is seen that mesoscale eddies may also be a major factor in ocean heat transport. A quantitative analysis of the relative contribution of different mechanisms of poleward heat transport awaits new measurements.

There are now more than a million bathythermograph temperature profiles of the upper ocean in the data archives. In the Northern Hemisphere, at least, a fairly good picture of the summer to winter heat storage process is beginning to emerge. Figure 4 is an estimate from A. H. Oort and T. H. Vonder Haar (1976) of the average rate of seasonal heat storage by the oceans as a function of latitude and season. The rate is given in watts per square meter as an average for the entire area at each latitude, including land as well as ocean.

The heat stored at any given place need not be entirely due to local heating. Ocean currents

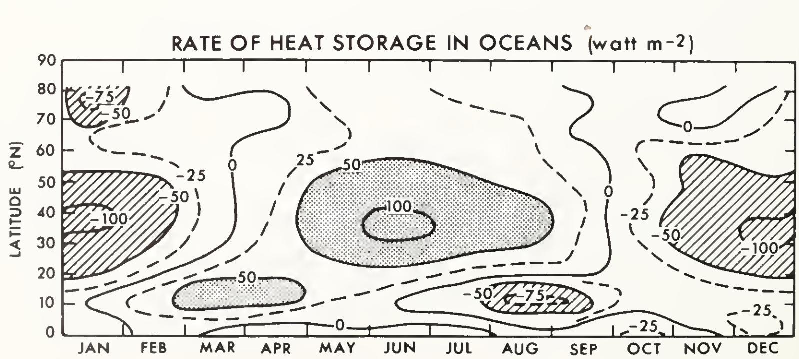

Figure 4. The rate of heat storage per unit area of the globe, including land and sea. (Oort and Vonder Haar's estimate from bathythermograph data, 1976)

change seasonally and this can cause an annual redistribution of heat in the upper ocean. A clue that this process may be important can be found in the Figure 4 seasonal heat storage diagram. In mid-latitudes, the rate of heat storage is at a maximum at the summer solstice (about June 22nd) and at a minimum at the winter solstice (about December 22nd). Heating changes sign at the equinoxes (about March 21st and September 23rd). This behavior is understandable if the sun is the major factor in adding heat to the water column. On the other hand, in the tropics, at 15 degrees North, maximum heat gain takes place three months earlier (Figure 4). Maximum heat loss is at the autumn equinox rather than in winter. The work of G. Meyers (1975) at the University of Hawaii suggests that this odd tropical heat storage pattern can be explained by changes in ocean currents induced by seasonal changes in the intensity of the trade winds.

Heat storage at mid-latitudes is largely confined to the upper 100 meters of the water column, making it relatively easy to measure. Seasonal changes in temperature profiles of a site in the North Pacific are shown in Figure 5. In winter, the mixed layer extends down to nearly 100 meters; in spring, the mixed layer becomes shallower. At some sites, the transition from a deep to a shallow summer thermocline can be quite abrupt in any individual year. Despite the summer heat, wind mixing keeps the temperature uniform within a small mixed layer close to the surface. When the intense summer heat ends, convective overturning adds to the effect of wind mixing and the mixed layer deepens abruptly.

The difference in area between the September and March temperature profiles in Figure 5, if expressed as degrees of temperature times depth in meters, is about 400 degree-meters. This area represents energy stored in the ocean during summer and released during the winter. It is equivalent to 1,600 million joules, or watts-seconds, per square meter of ocean surface. To convert this amount of energy into household terms, we can divide by the number of seconds in an hour, and get 440 kilowatt hours.

$$\frac{1{,}600 \times 10^6 \text{ watts-seconds}}{3{,}600} = 440 \text{ KWH (kilowatt hours)}$$

Let us compare solar and electrical heating. For a good round number, we picked the Consolidated Edison consumer rate of 10 cents per KWH in New York City. At the site shown in Figure 5, the total season's heat storage would cost $44 per square meter. In other words, the energy stored from summer to winter in a square meter of mid-latitude ocean is comparable to the energy used by a typical American household for cooking and heating hot water for a month.

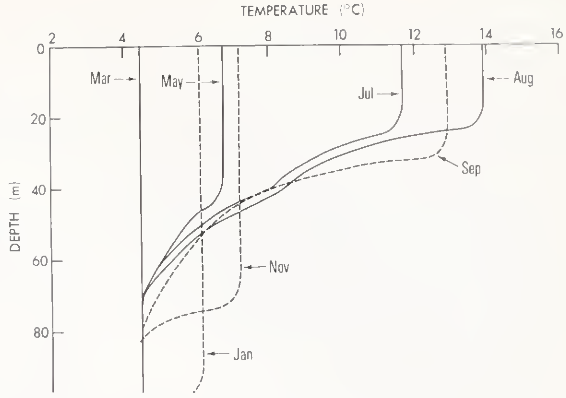

Figure 5. Temperature profiles at 50 degrees North, 145 degrees West in the North Pacific. (After Knauss, 1978)

In the 1950s, Bunker made some measurements of the way in which summer heat storage is taken up by the atmosphere in winter off the east coast of the United States. Using Woods Hole Oceanographic Institution aircraft, he traced the trajectory of cold air masses moving out over the Gulf Stream. Over the continental shelf near the shore, the difference between the temperature of the air and that of water can be very large, and the air is still too cold to hold much water vapor. In this nearshore region, most cooling takes place by direct transfer of sensible heat. A turbulent, convectively unstable layer of air forms just above the water surface, which increases in depth along the air trajectory away from shore. Gradually, the temperature difference between the air and water decreases, but by the time the air has moved that far offshore it has warmed up enough for evaporation to be effective. At this stage, evaporative cooling becomes dominant, providing a second-stage process for energy transfer from the ocean to the atmosphere. The two-stage process measured by Bunker allows energy transfer in winter to extend far out into the ocean.

Unfortunately, or fortunately, depending on whether or not you like cold winters, the winter transfer of energy to the atmosphere in mid-latitudes does not help very much if you live in the center or on the east coast of a major continent. The seasonal heat stored in the summer thermocline is transferred to winds moving rapidly eastward offshore. The beneficiaries live on the other side of the ocean, in England or British Columbia for example. Seasonal heat storage in the ocean is at least as important in moderating the climate of Europe and the Northwest as the heat transport by ocean currents. That is, even if the ocean were completely without major currents, seasonal heat storage and the prevailing westerlies in the atmosphere would make European winters much milder than those of eastern Canada at the same latitude.

Historical data on seasonal heat storage in the ocean are not abundant, but the data that do exist indicate important year-to-year differences.

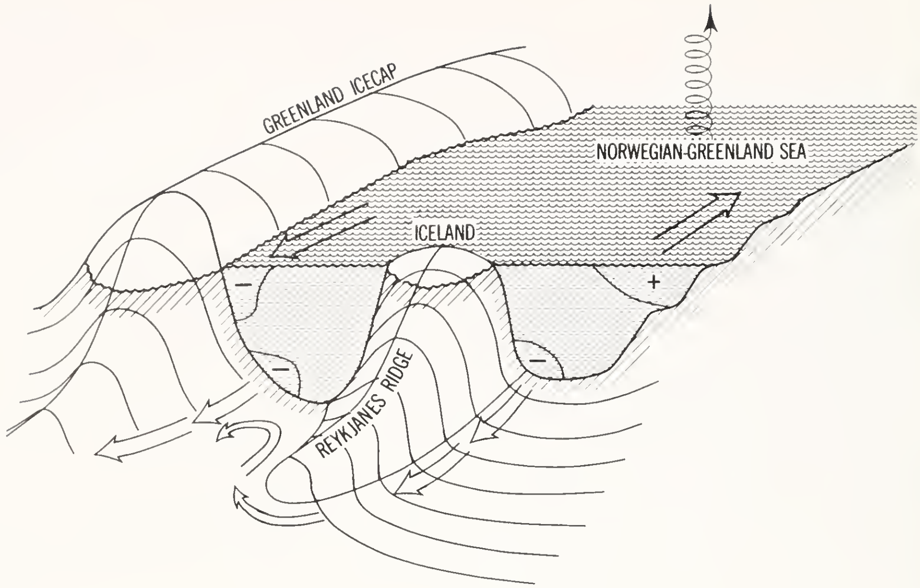

Figure 6. The main currents flowing in and out of the Norwegian-Greenland sea.

The articles in this issue by Warren White and Robert Haney, and Tim Barnett describe some of the short-term climatic variations that may be responsible.

The Subpolar Oceans: An Ocean Radiator

If ocean currents did not continuously bring in heat from lower latitudes, the average temperature of the subpolar oceans in high latitudes would drop each year, because the local energy input from the sun would be unable to offset the cooling process at the surface. Worthington describes some of these processes in his recent book (1976) on the circulation of the North Atlantic (see also *Oceanus*, Vol. 21, No. 1, p. 5). The Norwegian and Greenland Seas are separated from the rest of the North Atlantic by a submarine ridge that runs in a line from Greenland through Iceland to Scotland, perpendicular to the Mid-Atlantic Ridge. Warm surface waters enter the region in the Norwegian Current, which is an extension of the Florida Current, Gulf Stream, and Eastward North Atlantic Drift. Cold surface waters leave the Greenland Sea in the Greenland Current. Within the Norwegian-Greenland Sea area, extreme cooling of the warm waters of the Norwegian Current produces a deep, homogeneous mass of water. This water is distinguished from other deep-water masses in the world's oceans by its much higher salt content. As suggested by Joseph Reid of Scripps Institution of Oceanography, high salinity is partly the effect of the Mediterranean outflow, some of which may find its way into the Norwegian-Greenland Sea.

Within the last decade, measurements by Worthington and others have established an outflow to the south of the deep water of the Norwegian-Greenland Sea. The outflow takes place over two deep passes in the submarine ridge, one to the east of Iceland and one to the west (Figure 6). On a time scale of months or seasons, the outflow appears to be extremely steady. Subtracting the difference in heat content between the inflowing and outflowing currents (at the surface and in the deep water), Worthington found an approximate agreement between the net import of heat and the heat losses expected from surface cooling over the Norwegian-Greenland Sea.

New Satellite Measurements

William von Arx of the Woods Hole Oceanographic Institution was one of the early proponents of measuring sea level from satellites. The recently launched Seasat-A* carries a radar altimeter that measures distance between the satellite and the sea surface. Among its many other uses, altimetry should be helpful in understanding the ocean heat balance. To illustrate the principles, let h_a be the altitude of the satellite above the sea surface. Then,

$$h_a = h_s - h_g - \Delta h$$

where h_s is the satellite height above a reference spheroid, a mathematical model of the shape of the earth developed by geodesists, and h_g is the deviation of sea level due to smaller-scale gravitational anomalies. Variations of h_g are the features of most interest to marine geologists. The physical oceanographer is most interested in the final term Δh, which represents the elevation of the sea surface associated with pressure gradients in the atmosphere and ocean.

Measurements (C. D. Leitao, N. E. Huang, and C. G. Parra, 1978) from a predecessor of Seasat-A indicate that formidable problems of

*Seasat-A became inoperative on October 9, 1978.

accuracy are being overcome and that the instrument is already capable of recognizing major features, such as the 80 to 100-centimeter rise in sea-surface elevation along the northern edge of the Gulf Stream. As shown many years ago (1955) by J. G. Pattullo, Walter Munk, Roger Revelle, and Elizabeth Strong, heat storage is a major factor in seasonal variations at sea level. The summer thermocline consists of lighter water and tends to float above the main thermocline (Figure 7). Using direct measurements of the temperature profile in the upper ocean along shipping routes as calibration, satellite altimetry may eventually allow us to map heat storage globally on a month-to-month basis.

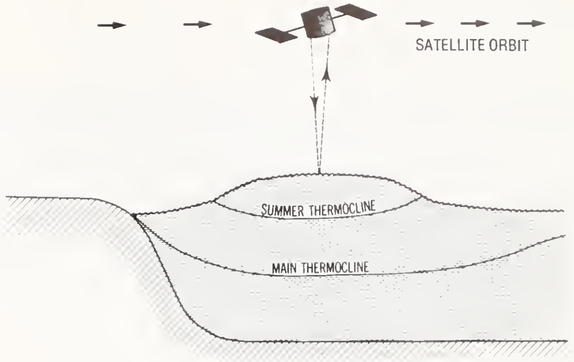

Figure 7. A possible future application of satellite radar altimeters to measure the summer thermocline.

Poleward Heat Transport

Using weather reports from shipping over a 25-year period, Bunker and Worthington have estimated (1976) the surface heat balance for the North Atlantic in a much more detailed way than has been possible before. Adding up the solar input at the ocean surface, and subtracting cooling due to evaporation and other effects, they estimated the heat gain in the tropics and the net heat loss in the Subpolar Zone. From their results (1976), I have calculated the poleward heat transport by ocean currents required for a long-term balance. The results are shown in Table 1, where they are compared with an earlier estimate made by H. U. Sverdrup (1957). His calculation is based on climatological data from the decades before World War II. Considering the differences in details of the calculations, the agreement is surprisingly close. Both estimates show that heat is transferred from the South to the North Atlantic. Northward heat transport continues to increase from the equator to 20 degrees North, since this is an area of net heat gain.

North of 30 degrees poleward heat transport is depleted by net losses through the ocean surface, and continues to decrease poleward. According to Table 1, the North Atlantic is transporting nearly 10^{15} watts poleward at middle latitudes. Dividing by the number of seconds in an hour,

$$\frac{10^{15}\text{ watts}}{3{,}600\text{ seconds/hour}} = 2.78 \times 10^{8}\text{ KWH/S.}$$

Multiplying the poleward energy transfer by the electric heating equivalent of 10 cents per kilowatt hour, we find that the North Atlantic is transporting $27.8 million in energy per second poleward in mid-latitudes. Even though the Florida Current and the Gulf Stream are probably the main conduits for this poleward heat flow, the east coast of North America receives very little benefit. The heat energy is on its way through, so to speak, and is already addressed to our neighbors in Iceland and northern Europe.

Vonder Haar and Oort have developed a completely different heat balance method. New satellite measurements of solar long- and short-wave radiation at the top of the atmosphere provide a requirement for the total poleward heat transport by the ocean and atmosphere combined. They then used the standard meteorological observational network to obtain an independent estimate of the contribution of the atmosphere alone. The difference between the total satellite-derived transport and the atmospheric poleward transport is the oceanic contribution.

Although Sverdrup's calculation for the North Atlantic is similar to Bunker and Worthington's, his estimate for the oceans of the Northern Hemisphere is quite different from Vonder Haar and Oort's satellite-based estimate. To resolve this puzzling discrepancy, direct measurements of heat transport are needed. With this in mind, Oort of the Geophysical Fluid Dynamics Laboratory at Princeton, New Jersey, and Henry Stommel of the Woods Hole Oceanographic Institution have recently proposed Project Heatflux for the latter part of the 1980s. The problem is to find a suitable method to measure north-south velocity and temperature across an entire ocean basin along a line of constant latitude. The section running due east from Miami to a point in Africa just south of the Canary Islands might be a particularly good place to start. The Florida Current between the mainland and the Bahamas has been measured extensively already, and is very accessible for future monitoring. To make measurements along this

Table 1. Heat balance estimates of poleward heat transport in units of 10^{14} watts.

	North Atlantic Poleward Heat Transport			
	60°N	40°N	20°N	O°N
Bunker and Worthington (1976)	1.2	6.6	8.2	4.0
Sverdrup (1957)	2.0	5.3	7.3	2.6

entire section is an enormous task, and is probably feasible only as an international effort.

Despite what we have learned during the last decade, the heat balance of the oceans is the most unknown element in the global heat balance. There is still much to be done. We have seen how the heat balance point of view raises fundamental questions and suggests viable observational experiments like Project Heatflux. We cannot afford to ignore the heat balance of the oceans in any well-planned study program of the oceans and climate.

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OCEAN TEMPERATURES: Precursors of Climate Change?

by Tim P. Barnett

The moisture and varying temperature of the land depends largely upon the positions of the currents in the ocean, and it is thought that when we know the laws of the latter we will, with the aid of meteorology, be able to say to the farmers hundreds of miles distant from the sea, "you will have an abnormal amount of rain during next summer," or, "the winter will be cold and clear," and by these predictions they can plant a crop to suit the circumstances or provide an unusual amount of food for their stock.

Lt. John E. Pillsbury from *The Gulf Stream,* 1891

After nearly 90 years, oceanographers and meteorologists are on the verge of testing Pillsbury's prophetic remarks. The scientific discoveries of the last several decades, plus some very obvious physical facts, give hope that knowledge of ocean properties, especially its surface temperature, may be used to effectively predict several months to years in advance the variations in certain aspects of the earth's climate.

We know that the atmosphere is in contact with the oceans over 72 percent of the earth. If the atmosphere is sensitive to bottom boundary conditions, then it must be aware of and perhaps reflect oceanic changes that are known to occur. This is so because the atmosphere is essentially a huge heat engine (see page 18). At any one time, the amount of fuel (heat) stored in a vertical column of air extending from the earth's surface to the fringes of space is approximately the same as the heat contained in an equivalent column of ocean water, extending from the surface of the ocean to a depth of *only* 3 meters. Thus it is the ocean that stores most of the sun's radiant energy for later release to the atmosphere, thereby providing much of the sustenance needed to maintain the atmospheric system. We know that the ocean, because of its greater density and high heat capacity, changes rather slowly with respect to the atmosphere. Thus many scientists feel it should be possible to predict future oceanic behavior and thereby infer subsequent changes in the atmosphere.

There is, of course, more than one point of view regarding the oceans' role in the climate system. Some scientists argue that the ocean acts as a low pass filter on the high-frequency fluctuations of the atmospheric field. This, along with the idea that the ocean is a major atmospheric energy source, suggests that the sea is merely a stabilizing influence on global climate. In this role then, it does not appear to be an initiator of climate change. It may be added that without this source of negative feedback between the ocean and the atmosphere, the climate of planet Earth might be highly unstable.

If the ocean can initiate climate change, then some of the ocean variables, such as water temperature anomalies, should be effective predictors of atmospheric properties. The substantiation of this statement, while not proving the role of the ocean as an initiator of climate change, would make a strong circumstantial case for that conclusion. On the other hand, if none of the ocean variables can act as effective atmospheric predictors then we might conclude that the ocean is more or less a slave to the atmosphere — just following its directions.

Covariability of Ocean/Atmosphere Features

It is important to establish that variations in ocean properties, such as sea-surface temperature (SST), are related to similar changes in the atmospheric field. Although numerous examples of the coherent relations between ocean and atmosphere could be given, a few here will suffice.

A principal component analysis of the Northern Hemisphere surface temperature field is shown in Figure 1. This analysis method defined the normal modes of variation in a data set from 454 stations scattered over the land and ocean areas between 15 and 70 degrees North for the period 1950 through 1977. These modes, when displayed in map form (Figure 1), show the regions of the hemisphere where temperature variations are coherent. For instance during winter, ocean temperatures in a large region of the central Pacific, as well as air temperatures over northwestern and

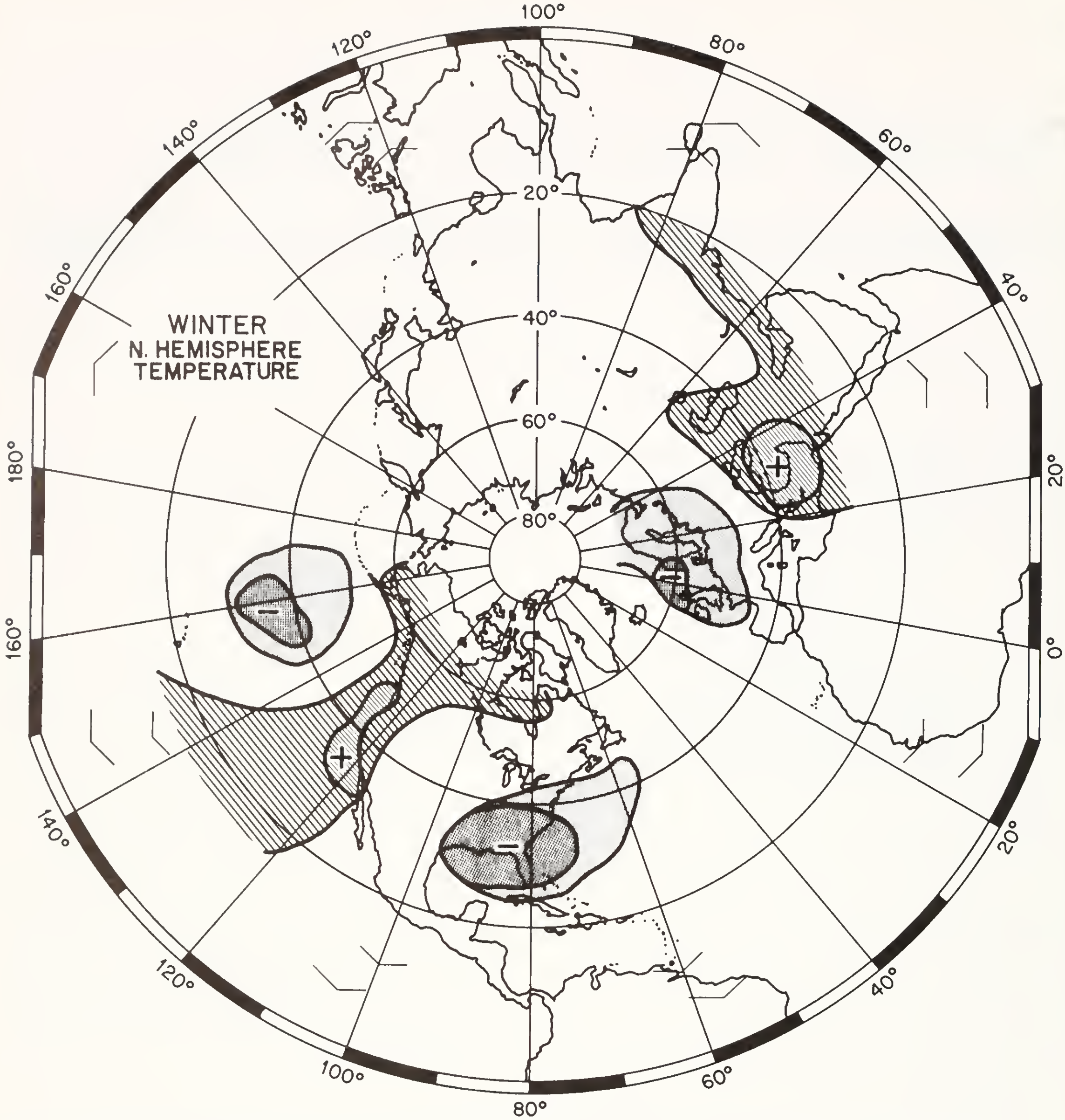

Figure 1. Wintertime temperature in the Northern Hemisphere. The stippled and hatched regions show areas where temperature variability is most highly correlated. The regions indicated plus will be warm, while regions indicated minus will be cold. The pattern of variability accounts for 18 percent of the variance in the hemispheric temperature field.

southeastern North America, vary in unison. This variability is linked to fluctuations in the air temperature in Europe and the Middle East. The analysis also provides a sense of the phase of the variation. Figure 1, for example, shows that when the water in the central Pacific is colder than normal, the air temperatures over the southeastern United States and northern Europe are colder than usual. Similarly, temperatures along the west coast of North America and in the Mideast region of the Mediterranean are warmer than normal.* Thus changes in ocean temperatures occur simultaneously with changes in air temperatures over the continents in the Northern Hemisphere.

Another demonstration of the close relationship between changes in ocean temperature and changes in the atmospheric field is provided in Figure 2. In this case, historical records of atmospheric pressure anomalies and ocean temperature anomalies in the North Pacific are used to construct a regression model whereby SST anomaly fields may be converted directly into fields of 700-millibar height anomaly. The figure shows a typical example of the model's ability to *specify* the character of the atmosphere immediately overlying

*In fact, this is the temperature pattern that has prevailed over the last two winters.

an SST anomaly from the SST data alone. The regression model also can be built in the opposite direction. That is, if one knows the atmospheric anomaly, it also is possible to *specify* the nature of the sea-surface temperature anomaly field. Again the simultaneous relation between ocean and atmospheric fluctuation is apparent.

The close coupling between the ocean and the atmosphere is not confined to these mid-latitude examples. Indeed, some of the strongest ocean/atmosphere interactions occur in tropical regions: particularly the tropical Pacific. Most people have heard of the phenomenon called El Niño, which generally connotes a warming of ocean waters just off the coast of South America and the subsequent diminishing of the local anchovy populations (see page 40). We now know that the El Niño phenomenon is only one part of a large-scale air/sea interaction that occurs across the entire tropical Pacific and most likely extends, in some measure, throughout the entire Southern Hemisphere with possible linkage to the Northern Hemisphere. During these large-scale air/sea interactions in the tropical regions, the surface waters warm considerably; not only along the coast of South America but along the equator to the date line — a quarter of the way around the earth. The changes in temperatures are on the order of 2 to 4 degrees Celsius, which is unexpectedly large for what is normally thought to be a quiescent tropical region. Accompanying these changes in water temperature are massive changes in the east-west slope of sea level across the entire Pacific basin. Both of these oceanographic features accompany equally massive changes in the distribution of rainfall in the tropical Pacific. Some regions that are normally dry experience exceptionally heavy rains and vice versa. The oceanic fluctuations also are closely linked to significant changes in the entire trade wind field. In extreme cases, the field is affected over its entire 50-million-square kilometer area. Close numerical scrutiny of these fluctuations shows a complex picture of action and reaction within the ocean/atmosphere system in this region. Although a complete understanding of these interactions is still lacking, it is clear that the equatorial ocean and atmosphere are inextricably linked.

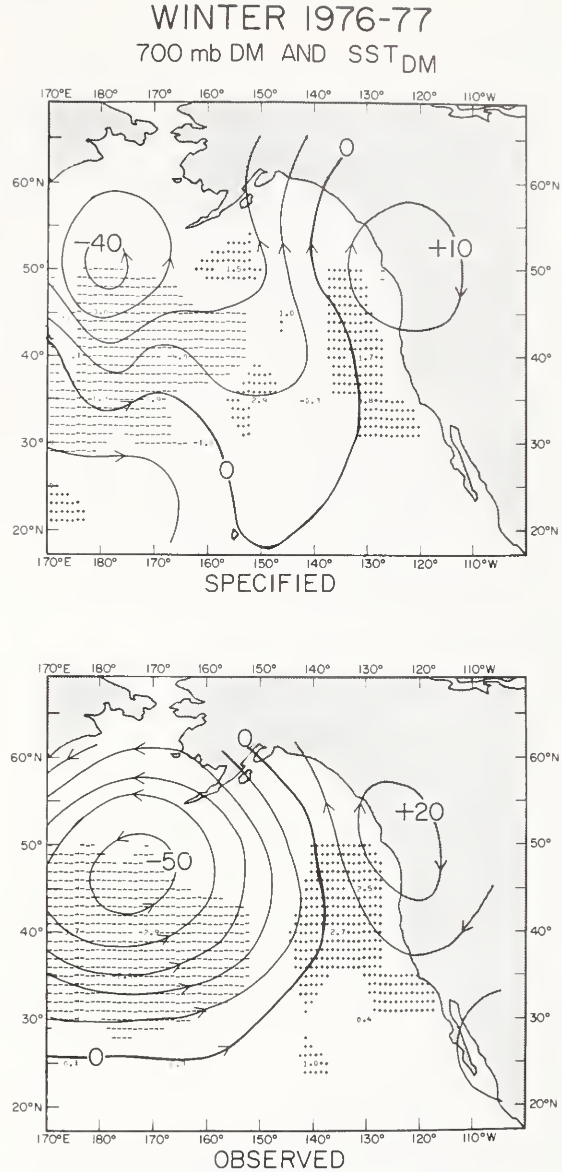

Figure 2. Specification of 700-millibar height anomaly (Departure from Mean) fields from sea-surface temperature anomalies (dashes and pluses) compared with observations. It is possible to use the 700 mb data to make a simultaneous specification of the sea-surface temperature field. (After Namias and Born, 1972)

Coupling Mechanisms

We have seen that the atmosphere and ocean are closely linked on a contemporaneous basis. A rudimentary knowledge of the physical processes responsible for this coupling is available. The ocean affects the atmosphere largely through air-sea heat exchange. Both sensible* and latent heat are given off to the atmosphere, although the latter is generally the larger of the two quantities. Strong areas of heat uptake by the atmosphere occur during the winter off the eastern margins of the Northern Hemisphere continents, when cold, dry air suddenly encounters a relatively warm ocean. Besides the air/sea heat exchange, the ocean can have another, slightly more subtle, influence on the heat budget of the atmosphere. Each year, the higher latitudes of the hemispheres lose more heat to space than is supplied to them by the sun. This

*Sensible heating refers to a process of heat transfer by conduction, while latent heating is associated with a change of phase of water (evaporation/precipitation).

deficit is made up by a transport of heat — both in the atmosphere and the ocean — from the abundantly supplied tropical regions, thereby maintaining a stable climate. Near latitudes 20 to 30, approximately half of the northward heat flux occurs in the oceans. Presumably the varying strength and distribution of ocean currents could affect this transfer of heat from the tropics to the mid-latitudes and thus influence the climate system (see page 18).

The atmosphere in turn directly affects the ocean, principally through the transfer of momentum in the lower boundary layer. At the present time, it is not entirely clear how the momentum actually gets into the ocean, but it can affect the supply of heat in the ocean through several different, well-known mechanisms; for instance, the momentum-driven ocean current systems. These motions, working against a temperature gradient in the ocean, can lead to a transfer of heat and a change in ocean temperatures. As another example, the rate at which the ocean actually gives up heat to the atmosphere (through the flow of either sensible or latent heat) is roughly proportional to the speed of the wind itself.

The physics associated with the air/sea heat exchange on large scales is complicated — both media being coupled in an almost symbiotic way. Additional difficulties arise when each of the physical processes is investigated in detail, since the actual mechanics and formulation of the processes are not fully understood. The scientific community is presently attempting to refine knowledge of, and more accurately evaluate, the principal mechanisms responsible for large-scale ocean/atmosphere coupling.

Does Predictability Exist?

A crucial question is: Can ocean temperature anomalies be used to predict features of the atmospheric field? A positive answer would strongly suggest, but *not prove,* that the oceans play a strong role in determining climate change. Unfortunately, a clear answer does not exist, although several relatively recent studies lead one to expect limited predictability from oceanic considerations. An example is found in the collected works of Jerome Namias of the Scripps Institution of Oceanography. Using the observed sea-surface temperature anomalies in the Pacific during a selected season, Namias projects the sea-surface temperature anomaly field expected during the *subsequent* season. Using the specification techniques mentioned earlier, the future sea-surface temperature field is then converted into a prediction of the overlying anomaly field of 700-millibar height. Using cross-correlations, the pattern of atmospheric anomaly over the Pacific is then used to estimate the expected atmospheric flow patterns "downstream," for example, over North America. This is basically the idea of "teleconnections" wherein events in one part of the atmosphere communicate their existence to and induce fluctuations in other parts of the atmosphere. In this case, the pressure anomaly distributions over the Pacific are related to their expected counterparts over North America. Thus a prediction of the pressure pattern is made one season in advance over the continent.

Given the pressure pattern, it is possible to infer and objectively compute the general features of the distribution of temperature and precipitation over the land mass. Additional atmospheric indicators are employed to touch up the forecast for subregions of the continent. Figure 3 is an example of Namias' prediction for the severe winter of 1976-77. The prediction is remarkable in that the preceding five years had the exact opposite distribution of anomalous temperature over the United States. Thus the break in the warm regime on the East Coast was well predicted. Although Namias' forecasting skill on the average over the last five years is definitely above that expected by chance, which suggests that the method has some validity, it is far from reliable.

Another method of prediction is analog selections (Barnett and Preisendorfer, 1978). Suppose one wishes to make a forecast for, say, winter. The idea is to find a previous fall in the historical record that closely resembles the current fall. To forecast the winter then, one would call for Nature to repeat herself; for example, the past winter would be forecast to reoccur. These simple concepts have been embodied in a complex mathematical formalism so that the current state of the climate is contrasted with past ones. A key element in defining the climate state is the distribution of SST anomalies in the oceans of the Northern Hemisphere. The rules for making analog selections are applied completely by computer with no human intervention. The resulting predictions of air temperature, based on runs over the last 24 years, have shown significant skill in forecasting the summer one, two, and four seasons in advance over much of the country. They also have the ability to predict the winter, particularly severe ones, one season in advance. For example, the severe winters of both 1976-77 and 1977-78 (Figure 4) were predicted by analog methods. Intuition as well as statistical studies show that the longer the historical data base from which one can draw analogs, the better the forecasting will be. Unfortunately, there are only a limited number of climatic realizations available in the historical data base, and this may ultimately limit the method. At the present time, we are evaluating whether the limited data base will allow us to determine how much of the observed forecasting skill is due solely to oceanic predictors.

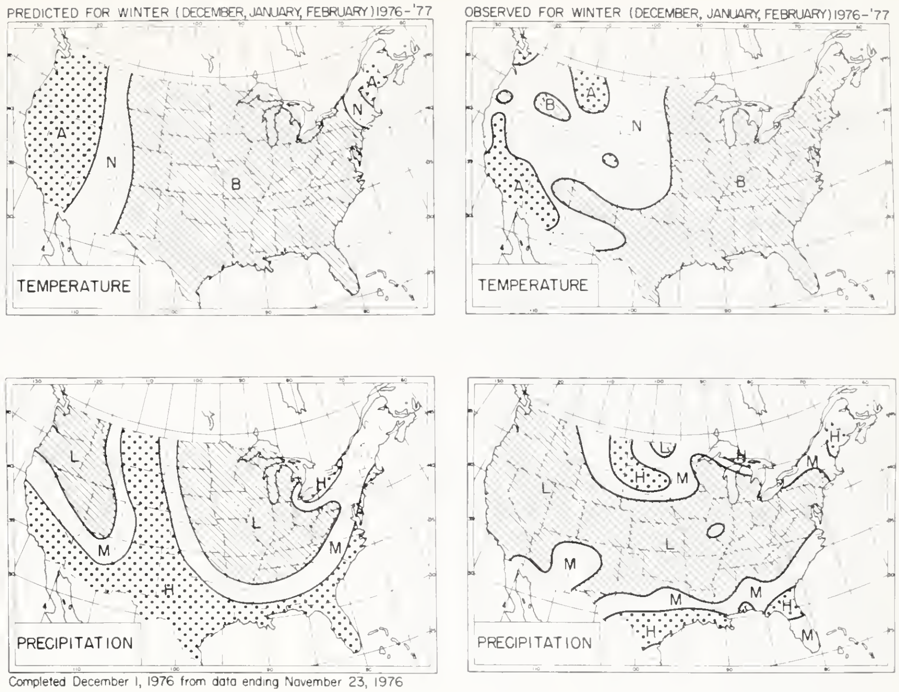

Figure 3. Observed and predicted temperature and precipitation for winter, 1976-77. The letters A, N, and B refer to temperature Above Normal, Normal, or Below Normal. Similar notation divides the precipitation field into Lower than Normal, and so on. (After Namias, 1978)

Another approach to climate forecasting is linear prediction theory, which is also called multivariate analysis, or regression analysis. This approach has been used several times to attempt climate forecasts. In one instance, R. E. Davis (1978) was able to show that the sea-surface temperature in the Gulf of Alaska could be used to forecast subsequent sea-level pressure anomalies over the same area. He also found that sea-level pressure in preceding seasons was a good predictor of pressures in subsequent seasons. It is not clear which of the two predictors, if either, is acting as an independent source of forecasting skill. Thus, while both are valuable, the study does not help much in determining if sea-surface temperature by itself is a "casual" predictor.

R. P. Harnack and H. E. Landsberg (1978) have developed a regression-type of forecasting. They use a large variety of predictors, including SST variables, to forecast air temperature anomalies in the eastern part of the United States. The results suggest that the forecasters have some skill because

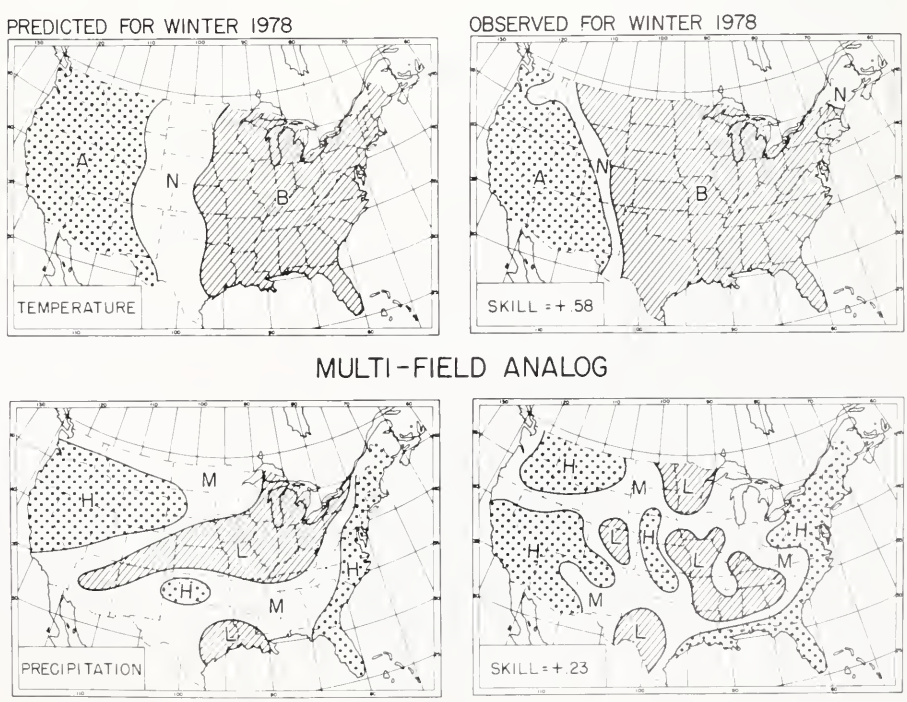

Figure 4. Predicted and observed temperature and precipitation patterns for winter, 1977-78, computed by analog methods. A skill of "0" would be equivalent to a forecast made by chance, while 1.00 would be a perfect forecast.

they have been able to account for a reasonable number of temperature anomaly occurrences in various categories. Unfortunately, the statistical significance tests they employ have many problems and weaknesses, making the results, while encouraging, hardly unequivocable.

A final approach that *may be* tried in the near future to predict monthly or seasonal weather trends is the application of the huge general circulation models (GCMs) of the atmosphere. To date, these computer models have only *simulated* climate change, although they are used to forecast weather one to five days in advance. In the climate simulations, a given distribution of sea-surface temperature anomaly is inserted in the model to see if the atmosphere has different average properties than in a case, say, where no sea-surface temperature anomaly exists. As one might guess, these simulations require a large, expensive computing effort, so not many have been done — and in those that have, the results are sometimes conflicting. There is at least one case where two different groups of scientists analyzed the same set of computer runs and drew opposite conclusions with respect to the importance of mid-latitude SST anomalies on the atmosphere. It will be quite a while before general circulation models can be pressed into service as effective forecasters of short-term climate fluctuations.

Future Needs

In view of the examples cited, it is still not possible to give a definite answer to the original question: Can ocean variables be used to predict short-term climate fluctuations? However, the results to date are encouraging. In the next few years, we will see considerable effort at extending them.

There is obviously a lot of detailed work that needs to be done to substantiate Lt. Pillsbury's conjecture. Much of the work requires the improvement of existing statistical and dynamical models. This improvement will come only as we obtain a deeper insight into the mechanisms responsible for the close coupling between the oceans and the atmosphere. The situation now is that we have numerous hypotheses that could describe this interaction and, therefore, lead the way to more sophisticated models. A large experimental research effort is underway around the world to test these hypotheses. Similarly, another major effort is being devoted to the analysis of existing data and to the statistical techniques that offer the brightest hope for short-term climate forecasting. It is an exciting time to be working in the area of climate research and prediction.

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The Dynamics of Ocean Climate Variability

by Warren B. White and Robert L. Haney

The oceans comprise more than 70 percent of the area of the earth and by virtue of their large heat capacity and sluggish nature are thought to be important to the year-to-year change in the world's climate. The natural time scale of the atmosphere is on the order of days and weeks, while for the oceans it is months and years. Both the ocean and atmosphere are an important source of heat, moisture, and momentum for the other, interacting in ways that are not well understood. However, studies completed during the last 10 years have determined that year-to-year changes in the location and strength of the major atmospheric centers of action over the ocean are related to fluctuations in the large-scale thermal structure underneath. Meteorologists have been able to relate this to changes in climate that take place over adjacent continents. As such, the key to the prediction of variability in climate may be found in the studies of the ocean.

Because of this association, an increasing number of oceanographers are focusing their efforts on studies of ocean changes that affect climate. Because this is a relatively new area of research, the results to date have been of a descriptive or qualitative nature, arising primarily from studies of historical sea-surface temperature records. The following is a short summary of the major results:

1. *Variations in temperature at the sea surface are often surface signatures of disturbances that extend well into the depths of the ocean (White and Walker, 1974).*

2. *Although disturbances in subsurface temperature can persist for years, they may develop over a period of a few months, principally in the autumn/winter seasons (Namias, 1959).*

3. *Disturbances in sea-surface temperature and surface wind patterns often have a definite space/time correlation with one another (Davis, 1976).*

To understand the strong interactions between the ocean and atmosphere, the mechanisms that couple the two fluid media have to be determined. This means formulating hypotheses that seek to explain how each responds to the other through their interchange of heat, moisture, and momentum. Some of the more interesting hypotheses concerning the ocean's role in this interchange have been paraphrased into the following questions:

1. *What is the relative importance of convection and mixing in altering the ocean's thermal structure, compared to the vertical and horizontal displacements induced by surface, wind-driven currents?*

2. *Do the wind-driven surface currents move more in the direction of the surface wind, or more to the right of it, as was theorized by Ekman in 1905?*

3. *Is the thermal structure of the upper ocean vertically displaced by the divergent action of the wind-driven surface currents, as was theorized by Veronis and Stommel in 1956?*

The answers to these questions are not only fundamental to understanding how the atmosphere and ocean interact on a year-to-year basis, but also to comprehending how the mean state of the ocean is maintained. The accepted ideas that presently form the basis of ocean circulation theory state that mixing dictates the thermal structure in the surface layer (upper 100 meters) while convection does the same in the deep waters (greater than 1,000 meters). The main thermocline then is altered by the divergent action of the wind-driven surface currents. This latter action derives from sea-level pressure systems, whose associated winds (parallel to the isobars) push the surface waters to the right (at the surface) and thereby create regions of open-ocean upwelling or downwelling within the thermal structure. This peculiar movement of the surface currents with respect to the wind direction is due to the influence of the earth's rotation, which applies a force (called the Coriolis force) to the wind-driven currents that deflect them to the right of the wind in the Northern Hemisphere, and to the left in the Southern Hemisphere. A sea level low-pressure system, with winds that move in a counterclockwise (cyclonic) direction, causes the

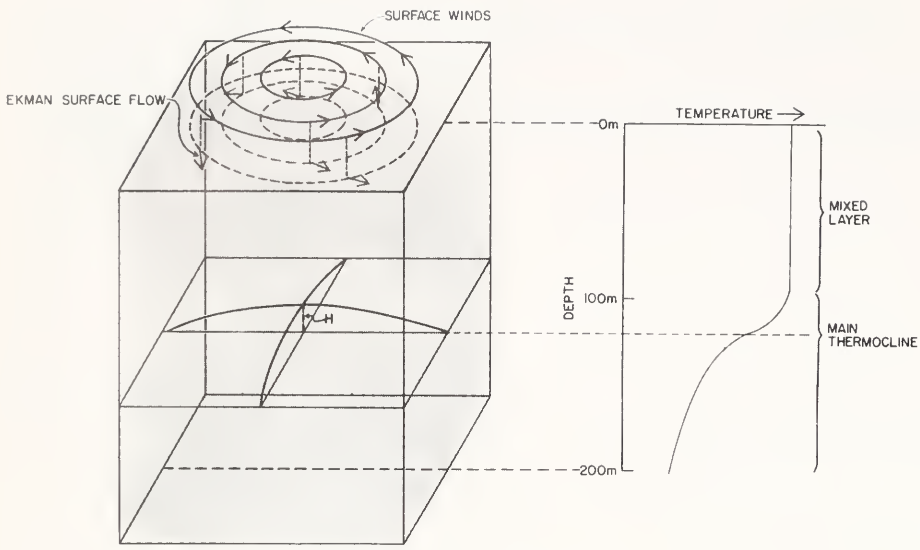

Figure 1. The classical wind-driven ocean circulation theory.

surface waters to diverge from the center of the pressure system, thereby causing the main thermocline to rise (Figure 1). This idea is being tested.

The Experimental Program

To address these questions, an experimental and theoretical program, called the Anomaly Dynamics Study, was begun in 1975 in the mid-latitude North Pacific. The program is cooperative, involving about a dozen investigators from different institutions working in close association on the problem of ocean/climate dynamics. It constitutes taking measurements for a period of five years of the surface wind-driven flow, the thermal structure in the upper 500 meters, and the surface wind and heating parameters needed to calculate the ocean/atmosphere exchange of heat, moisture, and momentum. The program also includes experiments with ocean circulation models that show how the upper ocean is supposed to respond to atmospheric forcing inputs. With the observed data, the models can be tested, hopefully answering the questions posed in the introduction.

The first year of the experimental program — 1975 — was dedicated to the design of a measurement program that would optimize the sampling rates and establish the reliability of the tools chosen for the experiment. This was essential, since an entirely new set of measurement tools was needed. Previously, field surveys usually utilized one or more research vessels that took a variety of oceanographic measurements in a local region for about a month at a time. For our purposes, a monitoring program was set up over a large portion of the ocean, not unlike meteorological networks already in existence over land. This was done in the mid-latitude North Pacific in a region (Figure 2) where much of the information on the statistical correlation between disturbances in surface temperature and sea-level pressure had already been obtained.

A new tool for measuring wind-driven surface currents was developed. It is a

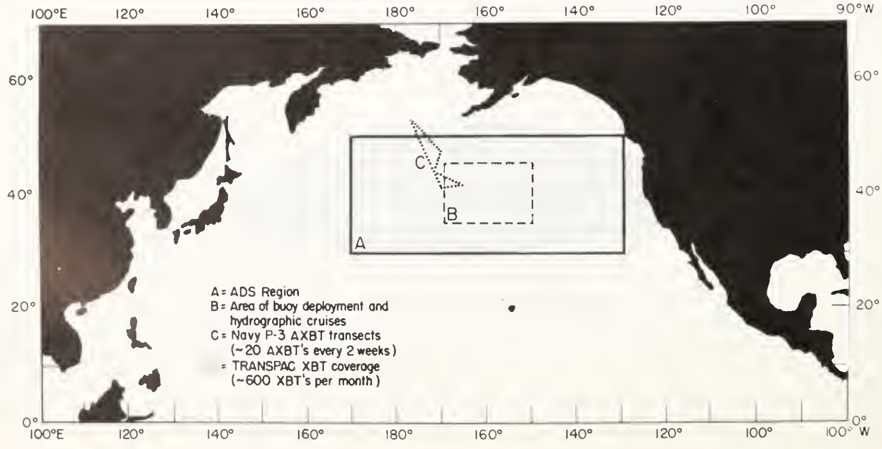

Figure 2. Location of the Anomaly Dynamics Study.

satellite-tracked, free-drifting buoy (Figure 3), containing a battery-powered transmitter whose position is monitored twice daily by the *Nimbus VI* satellite for a period of up to a year-and-a-half. A new program for measuring the thermal structure of the ocean (Figure 4) involved commercial ships-of-opportunity (between North America and Japan) and Navy P-3 aircraft, each having an expendable bathythermograph (XBT) system that drops a temperature-measuring probe into the ocean while the ships and aircraft are underway. The probe relays temperature depth information back to the craft. Another device utilized was the General Dynamics Monster buoy that measures the surface wind and surface heating parameters (Figure 5).

Figure 3. The satellite-tracked, free-drifting buoy, three-quarters of which is underwater when deployed. Standing next to the buoy is its designer, Gerard McNally.

The 1976-77 Disturbance

Preliminary studies in 1975 showed that the Anomaly Dynamics Study program was capable of making both the oceanic and atmospheric measurements needed to answer the questions mentioned earlier. The effort began in earnest in June 1976 and during the subsequent autumn/winter period provided the first complete measurement of a significant ocean/atmosphere disturbance. During the autumn and winter of 1976-77, the storm forcing and the sea-surface temperature (SST) were often two to three standard deviations from normal in the North Pacific (Figure 6). In both seasons, between 30 to 50 degrees North in the central portion of the ocean, sea-surface temperature was 2 degrees Celsius colder than normal, associated in some as yet unknown way with an atmospheric storm frequency that had four to six more storms per season than usual. What is perhaps most remarkable about these data is the persistence of the altered climatic conditions throughout the entire autumn/winter season. This strength and persistence had been only seen rarely in the last 30 years.

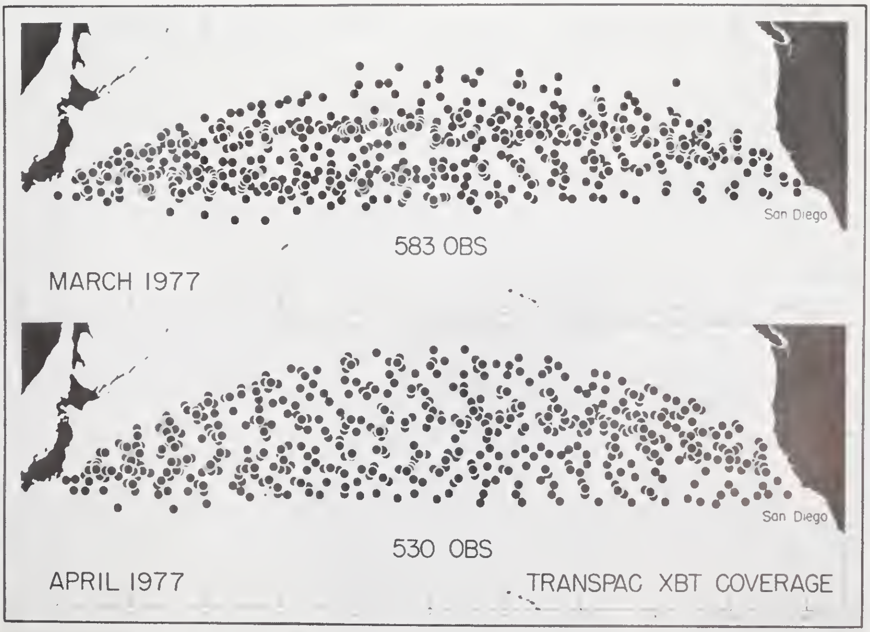

Figure 4. The North Pacific, showing the XBT observation coverage for March and April, 1977. The observations were taken by approximately 25 commercial ships-of-opportunity that ply the trade routes of the Pacific, and by Navy P-3 aircraft.

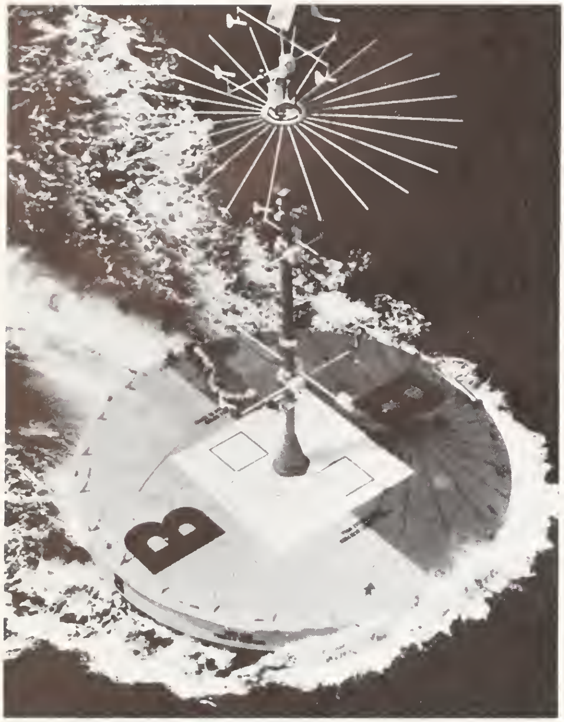

Figure 5. The General Dynamics Monster buoy, used to gather reliable and closely-sampled oceanographic and meteorological observations such as sea-level pressure, air and water temperature, wind speed and direction, as well as many other oceanic and atmospheric parameters.

The wind-driven surface currents during this time were measured by 32 satellite-tracked buoys, drogued at 30 meters depth. Figure 7 shows the trajectories of these buoys, along with surface currents that were remarkably laminar in nature, indicating the relative absence of horizontal turbulent processes that would have tended to separate adjacent buoys. Although unclear in this figure, the surface current flow depicted was wind-driven. This can be seen in Figure 8, which shows the monthly buoy displacements in relation to the monthly mean sea-level pressure. Clearly, the buoys were moving nearly in the direction of the wind (along the isobars) during the winter period. This is different from that expected (Figure 1). A distinct relationship between the surface wind and surface currents was found by comparing the monthly mean, vector-averaged, surface currents, as detected by the drifting buoys in Figure 7, with the average surface wind vector for that month (McNally and Kirwan, 1978). The resulting comparison finds the surface currents directed 15 to 30 degrees to the right of the surface wind on average, considerably less than that proposed by Ekman (45 degrees) in 1905. Incidentally, this observed angle is similar to that traveled by wind-driven icebergs (see page 47).

The thermal variability associated with this severe atmospheric disturbance was established by using data from the XBT temperature field measurement programs. Figure 9 shows the patterns of temperature disturbances (compared to the long-term monthly-mean norm) at the sea surface, 60, 120, 200, 300, and 400 meters, together with the patterns of sea-level pressure disturbances (compared to the same norm period as temperature). The upper panel shows a very intense low sea-level pressure disturbance during December, January, and February — indicative of the intense nature of the Aleutian Low Pressure System that is normally found there. This was associated with surface winds moving in counterclockwise rotation around the low pressure disturbance, similar to that shown in Figure 1. During the same period, the oceanic layers above

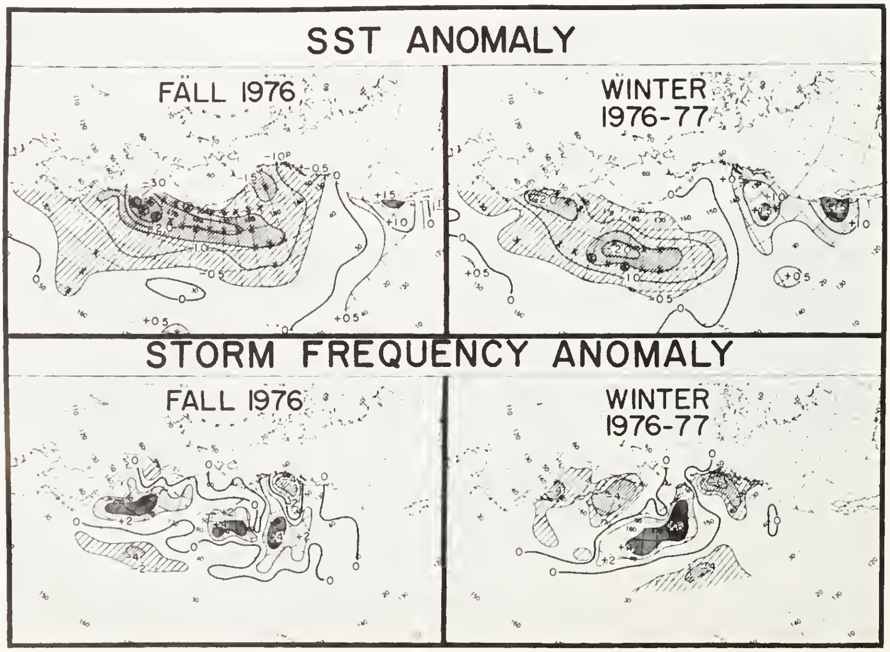

Figure 6. Seasonal mean maps of anomalous sea-surface temperature (°C) and cyclonic storm frequency over the North Pacific for fall and winter of 1976-77. The normal period of each map extends more than 10 years.

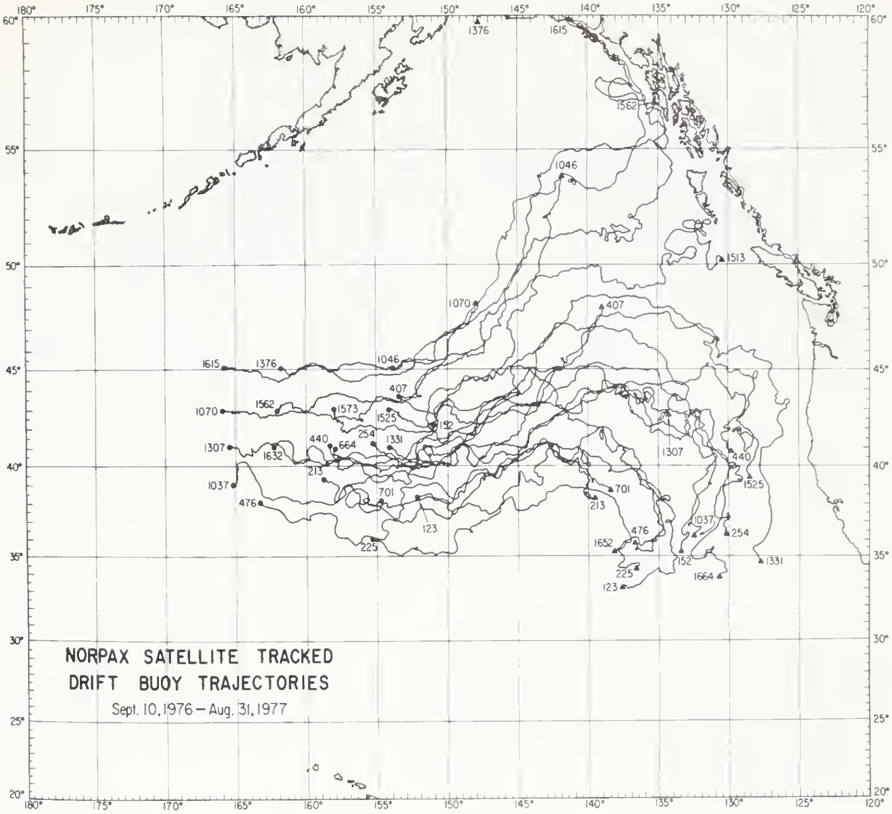

Figure 7. The trajectories of the satellite-tracked, free-drifting buoys deployed in June and September 1976, drifting eastward until August 1977. Each buoy was drogued at 30 meters depth. (After Kirwan and others, 1978.)

120 meters became very much colder than normal, while the deeper layers (in the thermocline) became warmer than usual. This is an important result — the opposite of what would be expected from the divergent action of the surface wind-driven currents where the thermocline displaces upward underneath the low-pressure disturbance rather than downward as indicated (Figure 1). A time sequence study of temperature profiles showed that the cooling at the surface and warming at depth (250 to 500 meters) occurred in association with a reduction in the vertical temperature contrast, perhaps induced by vertical mixing and/or convection processes both above and within the main thermocline. Although the analysis of this autumn/winter disturbance is not yet complete, the foregoing results represent a significant departure from what was expected (Figure 1).

Modeling the 1976-77 Disturbance

Prior to the Anomaly Dynamics Study program, both statistical and theoretical studies attempted to explain disturbances in sea-surface temperature at mid-latitude by using monthly and seasonal sea-level pressure data as input to simple near-surface ocean models. These efforts demonstrated that certain mechanisms, such as horizontal surface temperature displacement by wind-driven surface currents and surface heat flux, have accounted for some of the changes that have taken place in the sea-surface temperature field over the last 25 years. These studies also have shown that it is necessary to have models that consider subsurface temperature and currents in order to more clearly identify which of the many possible mechanisms are the most important. These models have been recently constructed.

A numerical simulation of the 1976-77 autumn/winter disturbance was conducted by Haney and others in 1978, using a 10-level ocean

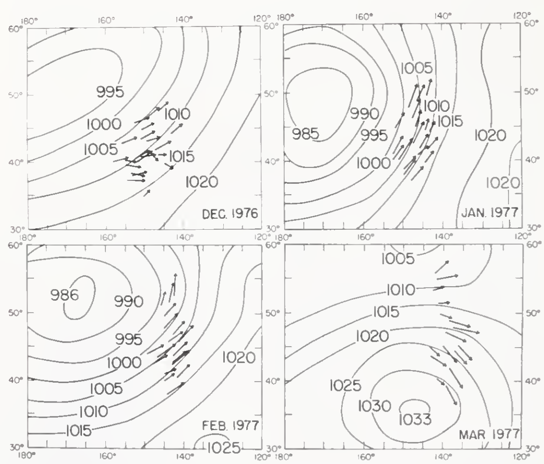

Figure 8. The monthly distribution of surface currents in the upper 30 meters of ocean (determined from the trajectories of the satellite-tracked buoys), superimposed on the monthly mean sea-level pressure map, covering December 1976 to March 1977. (After McNally and Kirwin, 1978)

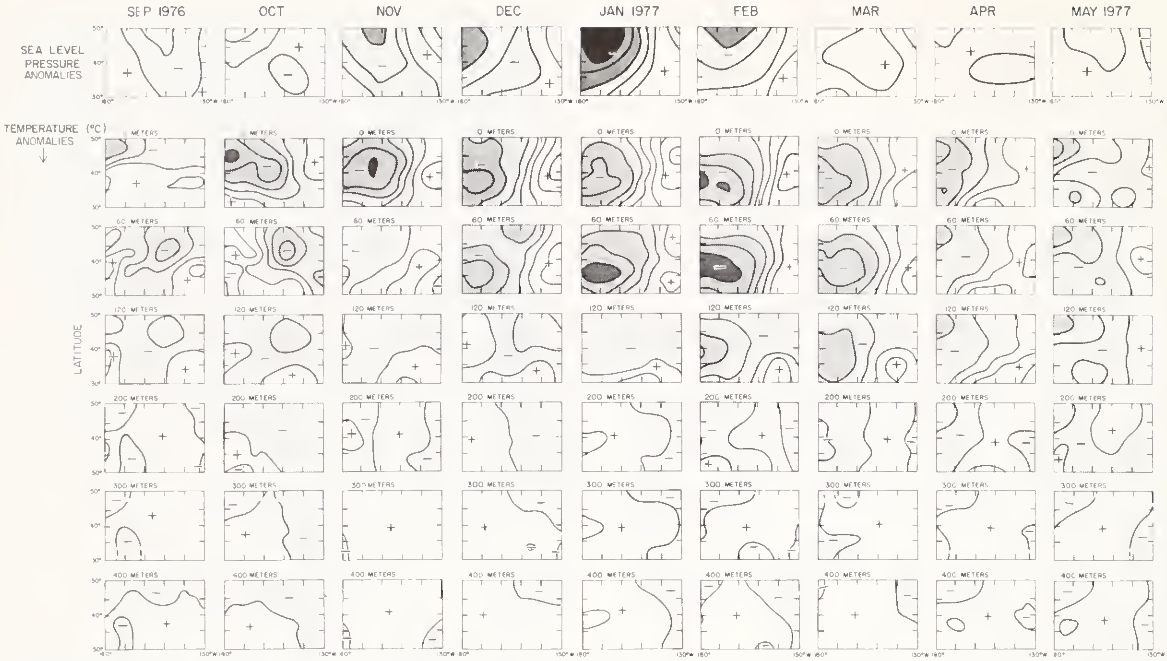

Figure 9. Time sequence from September 1976 to May 1977 of maps of anomalous sea-level pressure (upper panel) and of anomalous temperature at the sea surface, 60, 120, 200, 300, and 400 meters in the central North Pacific region. Contour of sea-level pressure is 5 millibars and of sea temperature is 0.5 degree Celsius. Negative anomalies are shaded. The normal period extends from 1968-1974.

model (based on the conservation of heat and momentum) in a closed rectangular basin the size of the North Pacific. The model is driven by observed atmospheric wind forcing obtained from sea-level pressure maps. Observed ocean temperature disturbances in the upper 500 meters are introduced into the model in the beginning; thereafter, the model attempts to simulate their observed evolution. In modeling the 1976-77 event, the numerical simulation started from the observed September temperature disturbance pattern and utilized the observed wind forcing from the monthly mean sea-level pressure pattern (upper panel, Figure 9). The resulting simulation (Figure 10, bottom) shows the development of a widespread cold disturbance in the surface layers which to some extent resembles that observed (Figure 10, top; also Figure 9). An examination of the model dynamics shows that the cold, sea-surface temperature disturbance in the model was generated by the displacement of cold water by anomalous southward-directed wind-driven surface currents. However, the model did not adequately simulate the deep, warm disturbance that occurred in the vicinity of the main thermocline. This has been tentatively attributed to the omission of convection and vertical mixing processes in the model. One wonders how the inclusion of these processes will affect the model simulation of the cold, sea-surface temperature disturbance. Work is progressing to insert these important dynamic processes into the model.

Results of Case Study

At this point, we are half-way through a five-year experimental program designed to test some of the mechanisms that are thought to be important for ocean/atmosphere climate dynamics on a year-to-year basis. In answer to the questions put

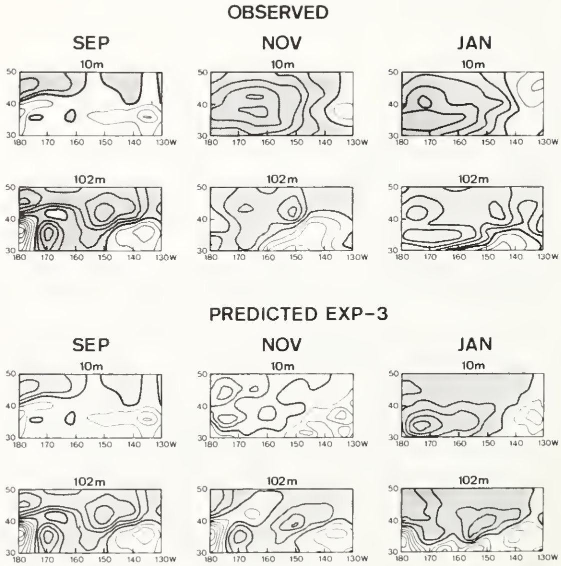

Figure 10. Observed and model evolution of anomalous temperatures at 10 and 102 meters from the same observed initial conditions in September, 1976. Contour intervals are 0.5 degree Celsius at 10 meters and 0.2 degree Celsius at 102 meters. Negative anomalies are shaded. (After Haney and others, 1978)

forth in the introduction, the results of the case study of the 1976/77 disturbance tentatively indicate the following:

1. The apparent effect of convection and/or mixing processes in the upper ocean dominated the vertical displacement of the thermal structure.

2. The wind-driven flow at the sea surface moved 15 to 30 degrees to the right of the surface wind, less than that predicted by Ekman in 1905.

3. Little evidence has been found that the thermal structure was displaced vertically by the divergent action of the wind-driven surface currents in the manner predicted by Veronis and Stommel in 1956.

These results indicate that the classical theoretical concepts do not explain this particular climatic disturbance in the ocean thermal structure. The signature of the thermal response suggests that convection and/or mixing were important in altering the thermal structure. This is presently being investigated with a view toward incorporating these processes into new ocean climate models.

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EL NIÑO—An Example of Ocean/

by James J. O'Brien

Every year at the equator off Ecuador, around the Christmas season, a tongue of the equatorial countercurrent sets southward from the Gulf of Guayaquil with waters that are 6 to 7 degrees Celsius warmer than those surrounding and much lower in salinity. This event is known as El Niño, which in Spanish means "The Child" or more specifically the Christ Child — symbol of the Christmas season. Periodically, the current is greatly strengthened so that it flows far to the south (to 12 degrees or more), displacing the cold Peru current and causing widespread destruction of plankton and fish. The ecological and economic implications are enormous. In Peru, the fish harvest is drastically reduced and seabirds die by the millions, severely limiting the annual guano take with its consequent effect on agriculture. Dead fish and birds rotting on the beach lead to the formation of hydrogen sulfide clouds which, when combined with sea fog, blacken the paint on ships, cars, and houses. In

Atmosphere Interactions

severe El Niño years, heavy rains cause flooding and widespread crop damage, adding to the catastrophes and misfortunes along the coast.

The causes of El Niño are not fully understood. Present scientific ideas relate the warming of waters off western South America to atmospheric events thousands of kilometers to the west in the central equatorial Pacific. Meteorologists have coined the phrase "teleconnections" to describe the apparent correlation between El Niño, cold winters in the United States and Europe, weakening of the Indian

Pelicans, cormorants, and gannets on Chincha Norte, an island off the coast of Peru. The droppings (guano) of the birds are rich in nitrate for fertilizer. Their sole food is the anchoveta. (Photo S. Larrain, FAO)

monsoon, heavy rains and unusual hurricane activity in the Pacific, and droughts in the Sahel.

Major El Niño events have been recorded in 1891, 1925, 1941, 1957-58, 1965, 1972-73, and 1976 — thus they do not occur in a regular, predictable cycle. But when they do occur, they are thought to cause poor food conditions in several areas of the globe. For example, in 1972, grain production in the Soviet Union was low; a continuing drought in the Sahel led to a demand for more food; and the El Niño conditions off Peru resulted in a low anchovy harvest. American readers may recall a sharp rise in chicken prices in early 1973, which was attributed to the fact that fish meal used as protein for dietary supplements was unavailable from Peru.

We have seen that El Niño is a massive inundation of abnormally warm water into the coastal regions of Peru and Ecuador. Figure 1 contrasts the normal (1971) and El Niño conditions (1972), showing the warmer eastern tropical Pacific Ocean. In Figure 2, the temperature anomalies at coastal stations along Ecuador and Peru are shown, with the appearance of warm water clearly distinguishable. Figure 3 shows the principal surface currents in the Pacific. There is a well-defined, narrow, northward-setting current along the west coast of South America called the Peru or Humboldt current. We have known for hundreds of years that the surface waters close to Peru are colder than what is expected at these latitudes (Figure 4). One might suspect that the icy waters of Antarctica are being swept northward. However, as early as 1844, U. de Tessan recognized that there is an upwelling (from 100 to 300 meters) of deep water along the coast (see *Oceanus*, Vol. 17, No. 4, p.3). Upwelling has been defined as ascending motion by which water from the subsurface layers is brought into the surface layer

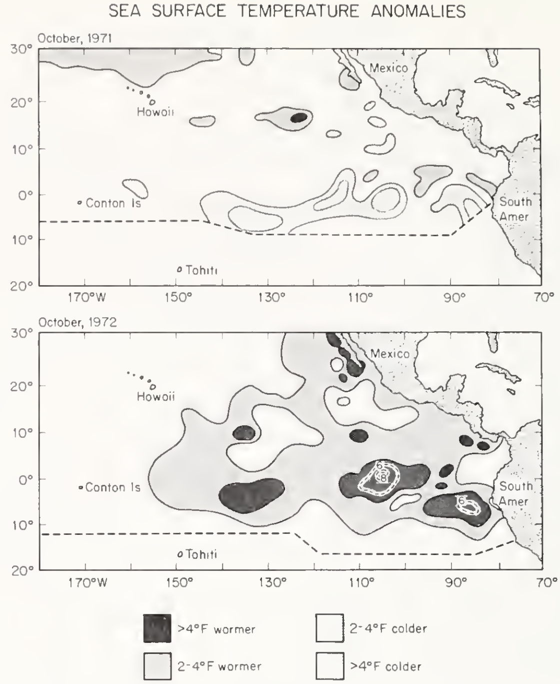

Figure 1. The sea-surface temperature anomaly is the observed temperature departure from the long-term climatic mean for the month. The year 1971 was considered "normal"; 1972, an El Niño year. Warm pools of water with anomalies of greater than 4 degrees Celsius were observed at the equator (110 degrees West) and off the coast of Peru. (Courtesy NOAA)

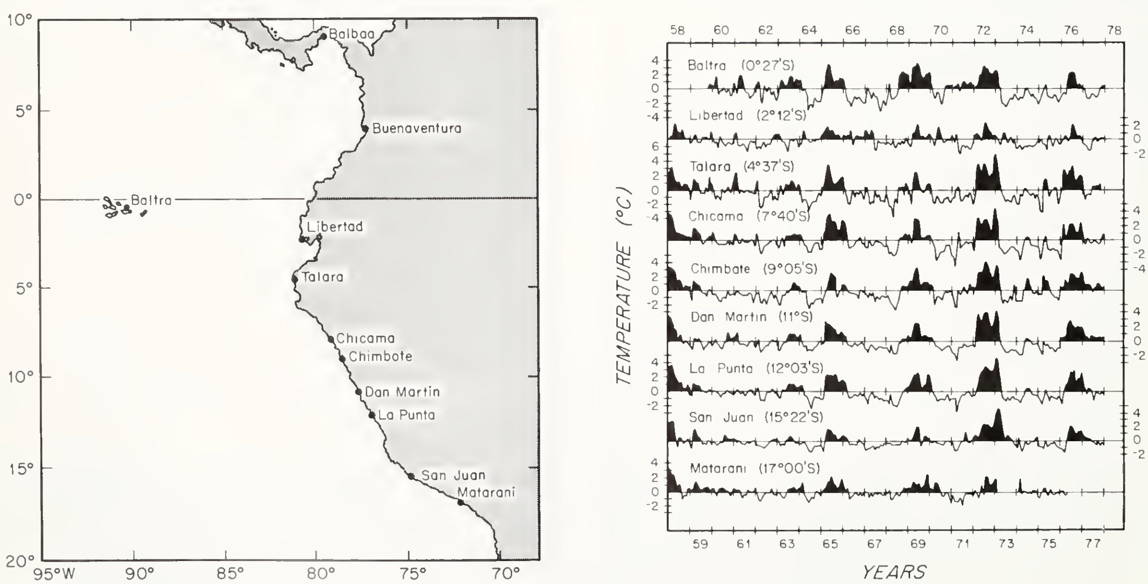

Figure 2. The map indicates coastal stations where ocean temperatures have been recorded. The monthly temperature anomalies are the deviation of the average monthly temperature from the long-term average. Therefore, the annual march of summer (warm) and winter (colder) temperatures has been removed. The El Niño years of 1958, 1965, 1972, and 1976 show warm water along South America. Scientists disagree on whether 1969 was an El Niño year. (Courtesy Dave Enfield and John Allen of Oregon State University)

and is removed from the area of upwelling by horizontal flow.

Coastal upwelling results when prevailing winds produce a condition of offshore flow in the surface layer near a coastal boundary. It occurs off the west coasts of continents and affects both the marine ecology and the climate of the adjacent land. Although coastal upwelling regions (for example, off California-Oregon, western South America, northwest and southwest Africa, and Portugal) cover only 1 percent of the world's oceans, John Ryther of the Woods Hole Oceanographic Institution has calculated that such areas account for more than half the world's commercial fish stocks. Lowered sea-surface temperatures in these areas suppress atmospheric convection and evaporation, producing a stable, but humid desert-like environment.

Why Coastal Upwelling Is Important

When the wind blows toward the equator off the west coast of continents, it sets up currents. Due to the effect of the earth's rotation, called the Coriolis force, there is a transport of water away from the coast. (This drift is known as Ekman flow after V. W. Ekman, who in 1903 studied why icebergs drift to the right of the wind.) Since the mass of water must be conserved, the water within 20 kilometers of the coast rises at 2 to 10 meters per day. The water comes up from 100- to 300-meter depths and is rich in dissolved nutrients. At these depths, there is not enough light for phytoplankton to grow, but at the surface, copious blooms of the tiny plants occur. Zooplankton, the animal forms of plankton, eat the plants and multiply. Fish are the next link in the food chain to benefit from the upwelling.

In middle latitudes, coastal upwelling is seasonal; off Oregon it lasts from April to October. Nearer the equator, off Baha or Peru, it occurs almost the entire year. As a result, the fish harvest can be bountiful (Table 1). In 1970, Peru accounted for more than a fifth of the total world fish protein. The collapse of the fishery in 1972 may have been partly the result of overfishing, but experts agree that El Niño was a major factor.

The Effect on the Anchovy Fishery

Very young anchoveta behave like zooplankton, feeding on the dinoflagellates* in the ocean. The anchovy larvae feed on copepods and small adult zooplankton, whereas the adult is herbivorous and feeds on phytoplankton. The young are very

*Microscopic, single-celled organisms, which may possess both plant and animal characteristics.

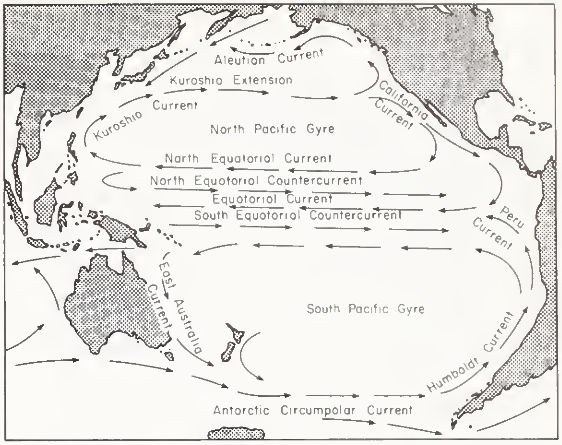

Figure 3. The current pattern in the equatorial region of the Pacific is more complex than that of the Atlantic, although to north and south similar enclosed circulatory gyres are formed. Recent research designates three west-flowing equatorial currents separated by two east-flowing equatorial countercurrents. (Courtesy Rand McNally Atlas of the Oceans)

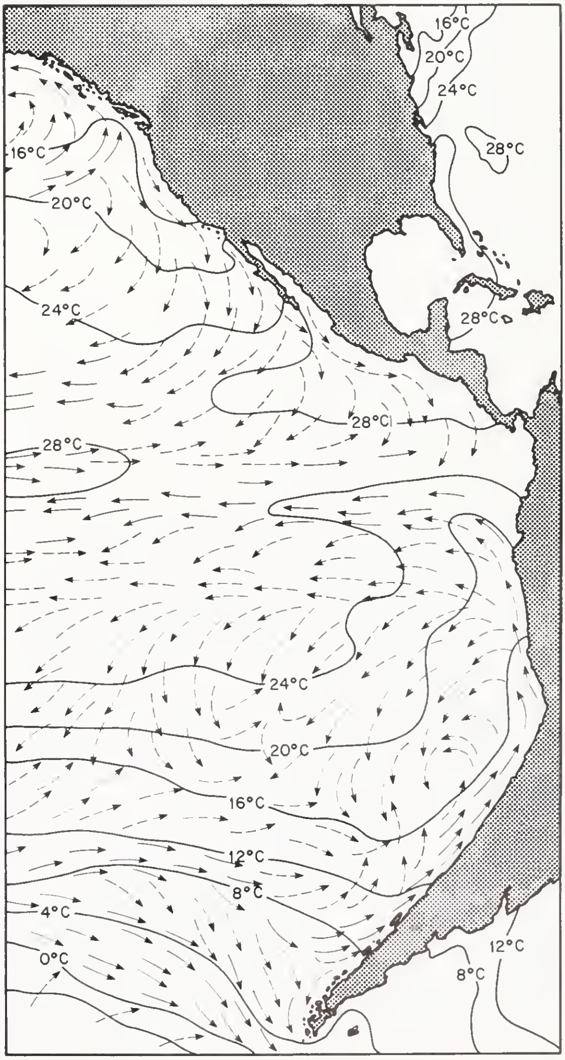

Figure 4. Mean temperatures in the eastern Pacific with indications of surface currents. Observe that the 16, 20, and 24 degree Celsius isotherms are far northward along the Chile/Peru coastline. (Courtesy Rand McNally Atlas of the Oceans)

Table 1. Annual Peruvian anchovy catch in millions of metric tons.

1960	3.3
1961	4.7
1962	6.3
1963	6.4
1964	8.9
1965	7.2
1966	8.5
1967	9.8
1968	10.3
1969	8.5
1970	12.3
1971	10.3
1972	4.7
1973	2.4
1974	4.2
1975	3.4
1976	4.3

susceptible to environmental conditions. Peruvian scientists have collected convincing evidence that spawning was at a low level in 1972-73. It is not known whether poor recruitment resulted directly from low spawning or heavy mortality at some juvenile stage.

It was previously thought that coastal upwelling off Peru ceased during El Niño. However, we now know that the prevailing winds which are necessary for upwelling are no different during El Niño years, therefore the coastal upwelling still occurs. Instead of pumping up cold, nutrient-rich water from 100 to 300 meters, all the water in an El Niño year is warm and low in nutrients; it comes from the equatorial region and cannot sustain the high primary productivity of normal conditions. It is this that has the devastating effect on the anchovy harvest.

A catch of anchovies being emptied into a fishmeal factory in Callao, Peru. (Photo Georg Gerster, PR)

The Warm Water Anomalies

Since the local winds are essentially the same in El Niño years, it is suspected that atmospheric and ocean climatic changes occur in remote regions. For years, scientists have disagreed over whether the trigger mechanism is at middle latitudes (30 to 50 degrees) or of equatorial origin. The late Professor J. Bjerknes of the University of California at Los Angeles pioneered studies of the 1957-58 El Niño, showing that massive changes in the large-scale atmospheric circulation over the equatorial Pacific are directly associated with El Niño.

Professor Klaus Wyrtki of the University of Hawaii has developed the most plausible explanation of the warm water anomaly off South America. Wind data from ships and islands indicate that in the year prior to El Niño there is a strengthening of the prevailing southeast trades over the equator in the central Pacific. These winds create a buildup of sea level toward the west in the same manner that wind can set up the surface of a lake. Associated with the onset of El Niño is a collapse of the equatorial trade winds (Figure 5). The sea level relaxes, but Wyrtki calls the most important response an "equatorial internal wave."

Simply stated, the ocean is a two-layer system with warm water near the surface and cold water below. The depth of the warm water is called the thermocline. Since its thickness is related to heat storage in the upper ocean, understanding its geographical distribution is a major climate problem (see pages 18 and 27).

During normal conditions, the thermocline is very shallow in the eastern tropical Pacific, with upwelling easily exposing the cold water below and bringing the nutrient-rich waters up into the euphotic zone (the layer receiving sunlight for the photosynthesis process). According to Wyrtki (and modelers such as H. Hurlburt, J. Kindle, J. O'Brien, and J. McCreary), when the equatorial trade winds relax, an internal wave trapped at the equator moves from west to east, raising the thermocline in the west and lowering it several hundred meters in

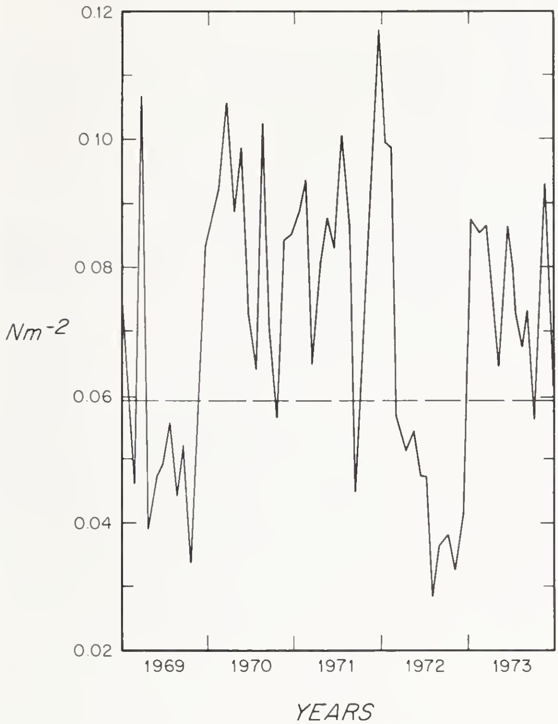

Figure 5. History of the east-west component of the wind stress over the central Pacific (140 degrees West to 180 degrees West). The dashed line is the long-term mean wind stress of about 12 knots. (Courtesy Klaus Wyrtki, Journal of Physical Oceanography, American Meteorological Society, Vol. 7, No. 6, Nov. 1977)

the east. A change in the ocean currents in the eastern Pacific accompanies a thickening of the warm water region. Instead of west- and northward setting currents, there are southward currents that advect the warm water along the Ecuador and Peru coasts.

The physical mechanism creating the internal wave along the equator is poorly understood because of insufficient data. Confined to within a few hundred kilometers of the equator, the wave travels eastward at 1 to 2 meters per second. If a method to detect it could be designed, then we might be able to predict the severe El Niño years a few months in advance. At present, many scientists from the Woods Hole Oceanographic Institution and other research centers are planning experiments for the early 1980s on this problem.

How El Niño Is Linked to U.S. Weather

Residents in the western part of the United States are well aware that poor weather forecasts are the result of a paucity of data from over the Pacific Ocean. It also hampers scientists in developing convincing theories of large-scale climate fluctuations. Two major atmospheric regions and their interactions have to be understood — the equatorial circulation and the mid-latitude waves.

The sun pumps excess energy into equatorial regions, with the upper ocean storing this energy and subsequently releasing it by evaporation (latent heat energy) or by transporting the heat poleward (see page 18). In the tropics away from the equator, low-level convergence zones (the Inter-Tropical Convergence Zone — ITCZ) and latent heat transfer from the ocean drive deep convective systems that pump heat into the upper troposphere. This heat is advected northward in a meridional circulation called the Hadley cell and is available for conversion to kinetic energy at middle latitudes.

Cloud pictures from satellites have made us aware of the wavy pattern of storms around the globe. In winter, there are usually five to eight storm systems in a narrow-latitude belt around the globe. In the upper troposphere, there is a series of troughs and ridges associated with cyclones. In the troughs, the cyclones intensify and advect large amounts of Arctic air southward. The waves can move or become quasi-stationary. When the latter occurs over the United States, residents of the Midwest and East experience frequent periods of frigid air that comes from northern Canada. Jerome Namias of Scripps Institution of Oceanography, Bjerknes, and others have explained how the Hadley cell, the mid-latitude wave system, and ocean interactions are linked. There are many ways to describe the events; the following is only one scenario.

When the trade winds collapse in the central Pacific, the Wyrtki mechanism occurs and large amounts of warm water appear in the eastern tropical Pacific. In addition, since strong winds enhance evaporation, the weakening of the trades reduces latent heat transfer, diminishes equatorial upwelling, and sea-surface temperatures rise. The ITCZ moves closer to the equator and creates increased rainfall.

Along with the change in the tropical atmosphere, there is a deepening of the semi-permanent Aleutian low pressure area in the Gulf of Alaska. Namias used this coupling to explain the abnormal winter of 1976-77. The strong Aleutian low produced a stationary wave pattern in middle latitudes, with a trough off the West Coast of the United States, a ridge over the Rockies, *and* a reinforced trough over the eastern states. Associated with the eastern trough were recurrent outbreaks of Arctic air and frequently heavy snow.

Equatorial Regions Hold the Key

El Niño is only one event in a complex web of climatic perturbations that is receiving increased attention from scientists. Large oceanic events also occur almost every year in other regions. In the Indian Ocean every year, the monsoon changes the

The port of Callao, Peru, with fishing boats drawn up awaiting a run of anchovies. (Photo S. Larrain, FAO)

direction and intensity of the Somali current. The timing of the Monsoon, which is important for Indian agriculture, is apparently linked to warm ocean anomalies in the Arabian Sea. In the Atlantic off the coast of Africa (from the Ivory Coast to Ghana), the summer sea-surface temperatures are colder than during the rest of the year. In July, almost every year, strong upwelling occurs even though local winds cannot support the Ekman drift. The variations in the Gulf of Guinea upwelling influence the rainfall in western Africa and may be partly responsible for the Sahel drought.

In general, the interaction between the atmosphere and the ocean is poorly understood. Meteorologists believe that the equatorial regions possess the information needed for improved long-range weather prediction. They have organized a World Weather Program for 1979 with the hope of obtaining substantially improved data from the tropics in order to test this hypothesis. Oceanographers are planning comprehensive field programs in the equatorial regions in the 1980s. These experiments may shed more light on the complex problem called El Niño.

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THE ROLE OF SEA ICE IN CLIMATE

by R. W. Stewart

The extent of ice cover on the earth has long been used as an indicator of climate. Evidence of the past existence of huge continental glaciers has been recognized as proof that at some stages in history the climate was much colder than it is now. The retreat of mountain glaciers within our lifetime (or at least within *my* lifetime — the retreat has not been so ubiquitous in the last couple of decades) is evidence that the present climate is warmer than it was just a few generations ago. Ice cover, however,

Iceberg in the Antarctic. (Photo A. W. Erickson)

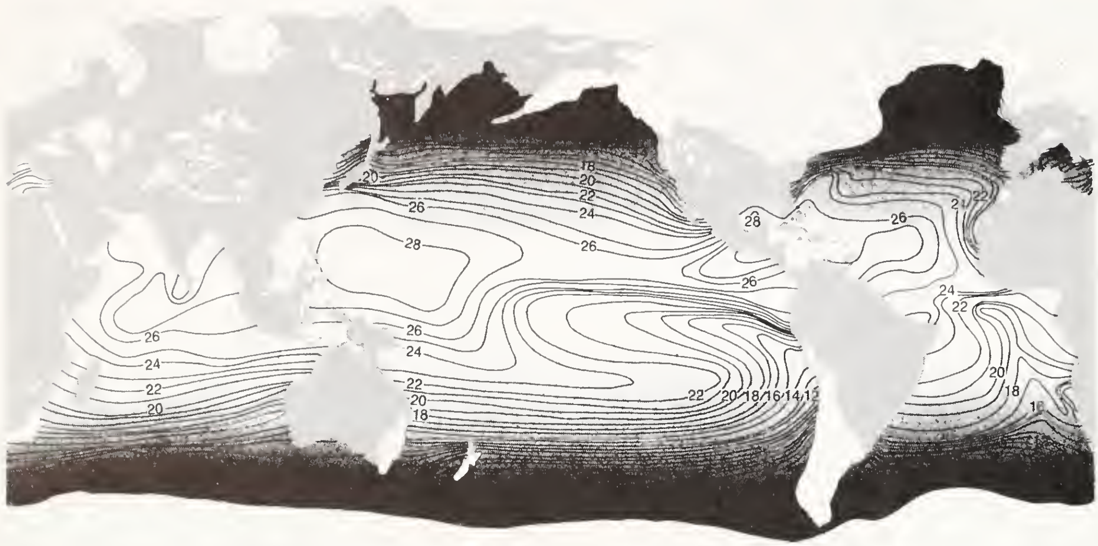


Figure 1. The world 18,000 years ago. White areas are terrestrial or sea ice. (Source: Lorius and Duplessy, 1977)

is not merely an indicator of climate change, it is also an agent of change.

If warm is considered good, ice — and in particular snow-covered ice — is miserable stuff. Bare sea ice will reflect about half the earth's incoming radiation, and the albedo* of snow-covered ice can reach 98 percent but averages about 80 percent (Chernigovsky, 1963). Like most surfaces, ice is essentially black in the portion of the infrared that is largely responsible for the radiative loss of heat from the earth's surface. It radiates heat away with full efficiency. Even in full summer, a surface at high latitude with an albedo of 80 percent is "trying" (against the effects of the atmosphere) to reach an equilibrium temperature of about –65 degrees Celsius. In comparison, moderately rough water, which will have an albedo of 10 to 15 percent at these latitudes, is radiatively trying to reach a summer temperature of about 25 degrees Celsius.

This characteristic of snow and ice provides one of the best known positive feedback mechanisms affecting climate. A decrease in the earth's average temperature, from whatever cause, will increase the proportion of surface covered by snow and ice. The resulting increase in the proportion of sunlight reflected away decreases the amount available to heat the earth and leads to a further cooling. This effect is so powerful that in some greatly simplified models of climate (M. I. Budyko, 1969; W. D. Sellers, 1969; S. H. Schneider, and T. Gal-Chen, 1973) a decrease in solar input of less than 2 percent — or less than a half percent in the mean surface temperature of the sun — leads to an earth that is covered with ice from pole to pole and, according to the models, irreversibly so. It is legitimate to question these models, because a great many important aspects are inadequately treated. Nevertheless, they do indicate that changes in snow and ice cover provide a powerful positive feedback mechanism. There is no longer any doubt that during the last ice age, which ended 10 to 12,000 years ago, the area covered by sea ice was much larger than it is today. In the Antarctic, for example, sea ice extended 1,000 kilometers north of the present limits. The snow and ice situation of 18,000 years ago is shown in Figure 1.

Positive feedback not only amplifies the effects of changes in external influences, such as the input from the sun, but serves to amplify the natural fluctuations that arise in certain systems. The atmosphere/ocean/ice system that determines climate is one such system. It generates its own natural fluctuations. Weather is one example, and it is probable that the climate changes that have been recorded during the last century or so are others. It is even possible that such fluctuations as the so-called little ice ages, which have time scales of centuries, and perhaps the full ice ages, which have time scales of tens of millennia, are further examples. Regardless of whether these climatic variations are caused by external effects, such as changes in the solar output or changes in the earth's

*The ratio of the amount of electromagnetic radiation reflected by an area of snow-covered ice to the amount of radiation incident upon it.

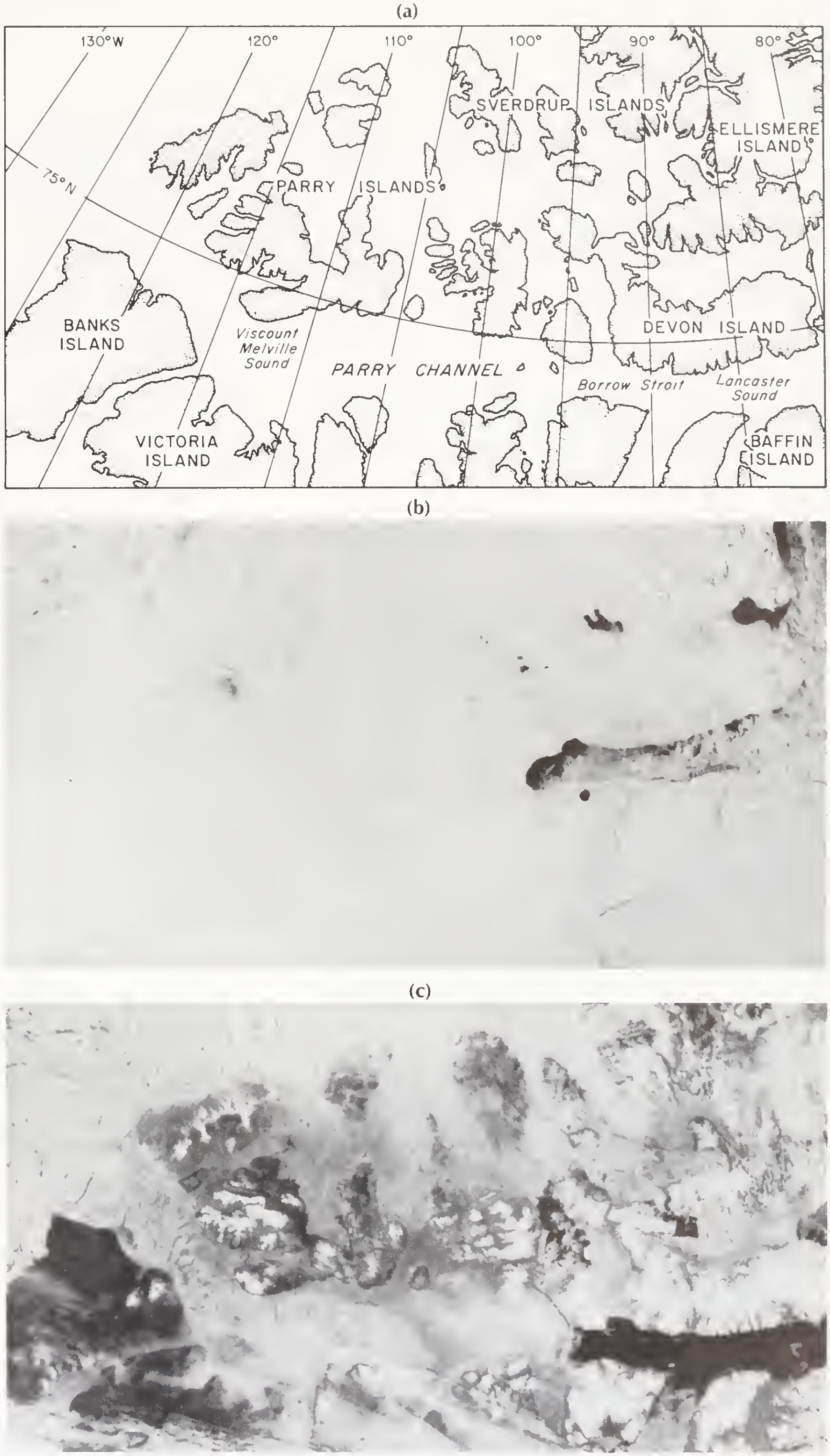


Figure 2 (a). Canadian area of satellite images near 75 degrees North, 100 degrees West shown in (b) and (c), and Figure 3. (b), National Oceanic and Atmospheric Administration satellite image on May 14, 1976. Except for a few open water areas, there is nearly uniform high albedo. (c), NOAA satellite image on July 3, 1976. Note contrasts between open water in the eastern Parry Channel, low snow-free land on Banks Island, bare sea ice, and the snow-covered highlands on Devon Island. (Source for b and c: Marko, 1977)

orbital parameters, or are produced entirely by the internal workings of the system, the amplifying influence of the snow and ice cover remains a factor.

Images obtained in space by satellite are revealing. Figure 2b shows the Canadian Arctic Archipelago as it appeared on May 14, 1976. Apart from a few areas of open water, the region is almost

uniformly white. Snow-covered ice and land (and a scattering of cloud) reflect away almost all of the incoming light. Figure 2c shows the same area on July 3, 1976. Snow fields at higher elevations on the islands retain the very high albedo. The major portion of the ice has now lost most of its snow cover and has a reduced, but still fairly high, albedo. Low-lying Banks Island (extreme left) appears quite dark and reveals the difference between sea ice and ordinary land. Barrow Strait and Lancaster Sound, which form the eastern part of Parry Channel, are open water and in this image appear almost black. This illustrates how snow and ice reduce the absorption of solar radiation.

The Winter Season

The radiation effects previously mentioned refer to the summer season, when ice cover principally influences radiation. The influence of sea ice on the transfer of heat and water vapor between the atmosphere and the surface is minor. There is not too much difference between the wet snow and ice that is characteristic of summer conditions, and open water (provided the open water is mixed deeply enough so that no shallow, warm layer can be formed).

In winter, the situation is quite different. The incoming solar radiation is either absent, or very weak. It does not matter whether the albedo is high or low. Under these circumstances, the ice cover allows the surface temperature to fall far below that possible in open water. This low temperature greatly reduces the radiation of heat into space. Thus, there is an overall reduction in cooling — equivalent to a warming — of the world. This also can be illustrated from satellite pictures. Figure 3 shows an infrared image of Lancaster Sound taken on December 15, 1975. In this image, darker areas indicate relatively strong radiation of energy into space. The dark areas are either regions of partially open water, or areas where the ice cover is so thin that heat flows through it relatively efficiently.

Although the difference between ice and open water in the winter is important from a radiation point of view, the most important effect of sea ice is probably in the differences of air/surface interaction. Since the surface of thick ice could be more than 40 degrees (usually at least 20 degrees) colder than surface water, the difference in the effect of the surface on the atmosphere is very great. The surface of thick ice will almost always be colder than the air some distance above it. This produces a low-level inversion with very little mixing into the higher levels of the atmosphere. Such exchange as there is transfers heat from the atmosphere to the ice, which in part supplies the heat required to maintain the negative radiation balance. (The remainder is supplied by cooling and freezing the water below and, to a lesser extent, from the cooling of the ice layer.) The vapor pressure is very low (one millibar or less).

Unlike heat flow over ice, that over water is upward (except in cases where the air mass moves rapidly from much lower latitudes) forming a thick, convective planetary boundary layer. The surface vapor pressure is much higher (about five millibars). The increased moisture in the atmosphere causes increased cloudiness, which in turn reduces the radiation loss from the surface. Whether or not such a reduction compensates for the increase in radiation from the relatively warm surface depends upon a number of complex atmospheric events. Not the least of these is the behavior of wind and the question of whether the resulting increased cloud cover occurs over the open water or over adjacent ice-covered areas.

How Ice Forms in Open Water

The difference between open water and ice cover has a very significant effect upon the atmosphere, and thus upon climate. The effects are far from simple and one should not, with any great confidence, predict the overall result of a change in ice cover. Simple arguments and simple models may produce answers resembling the truth, but one must be wary about complex feedbacks that could produce quite different results.

Figure 3. NOAA satellite infrared image on December 15, 1975. Open water in Lancaster Sound (Eastern Parry Channel) transmits much more heat to space than does ice-covered water or land. (Source: Marko, 1977)

Accepting that the extent of sea ice cover is an important parameter in the climate system, what determines it? Some of the relevant influences are revealed by the way in which ice forms in open water: heat is extracted from the surface by a combination of net radiation, heat transfer to the atmosphere, and evaporation. Unlike fresh water below 4 degrees Celsius, seawater with salinity above 24.8 parts per thousand has no temperature range (above the freezing point) in which the density decreases as the temperature decreases. Thus the extraction of heat from the surface results in convection in the water. This convection penetrates either to the bottom or to the depth of some upper layer of reduced salinity. Although density increases as temperature drops, near the freezing point only small changes in salinity are required to determine the stability of the water column.

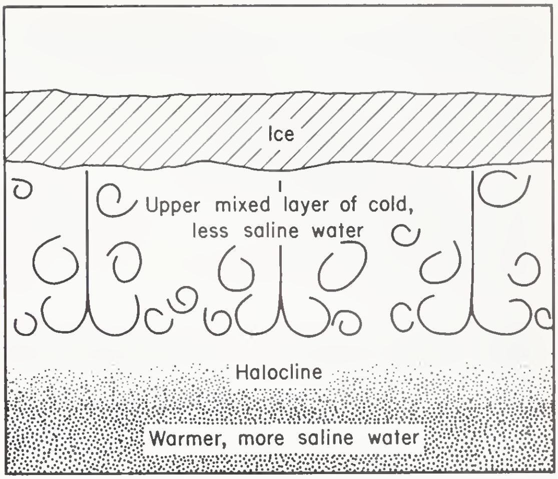
After the entire water column down to the base of the convection has been cooled to the freezing point, further withdrawal of heat results in freezing. Initially, ice appears in the form of minute particles called frazil ice. In disturbed conditions, these particles do not readily coalesce and are distributed in the water column. They settle on any object they encounter, be it the bottom, floating ice, or oceanographic instrument packages.

The ice crystals are lighter than water, so their concentration decreases with depth. Their distribution and surface concentration depends upon the amount of turbulence in the water. Eventually, either because of a reduction in turbulence during a calm spell or because the density of frazil ice becomes sufficient, the ice crystals begin to coalesce at the surface. An ice cover forms, with the ice building downward into the water. In forming ice, the salt is dispelled. This increases the salinity of the water in contact with the ice and provides a new instability to the water column, which leads to mixing at a greater depth than before freezing started. The increase in depth can be substantial if the underlying halocline* is weak. This increased depth of mixing adds to the heat available in the mixed water column, since the deeper, entrained water has a temperature above its freezing point.

Once the ice layer has formed, it provides an insulating layer between the water and the surface from which heat is lost to the atmosphere or by radiation to space. The insulating layer may be reinforced by an even more effective layer of snow.

The effect of the insulation is to permit the top surface to cool substantially below the freezing point of the water. Heat loss is considerably reduced. For example, E. Vowinckel and S. Orvig (1970) estimate that one-year-old ice about a meter-and-a-half thick in the central polar ocean grows about 33 centimeters per month; two-year-old ice approaching three meters in

*A zone below the mixed layer marked by a relatively large salinity change.



Salt-enriched water formed at the under surface of the ice creates convective turbulence in the upper layer, which erodes the halocline. Some of the warmer lower water is entrained into the mixed layer.

thickness, 10 centimeters per month; and multi-year ice more than three meters thick, 7 centimeters per month.

Thus ice formation and heat loss from the water beneath react to relatively small changes in circumstances. Given a certain depth for a major halocline, maximum ice formation occurs if the water above that halocline is kept well mixed

Frazil ice concentrating around the top of an oceanographic instrument lowered through a circular hole in the ice. The instrument, the frame of which is made of teak, extends down through the ice 2 meters, having 15 centimeters between bars. The small bottle at the bottom contains powdered milk and seawater, which is being pumped out through jets in the center bar to determine current flow. The lower part of the frame is below the upper mixed layer and remains uncoated because there is no frazil ice at these depths. (Courtesy Frozen Sea Research Group, Fisheries and Oceans, Canada)

The edge of loose ice in the Canadian Arctic. The scattered white objects in the ice-free area are beluga whales. (Photo by Kerry Finley, LGL Ltd., Toronto. Courtesy Polar Gas Project)

throughout the early part of the cooling season, so that the whole upper mixed layer is brought down to the freezing point before ice forms and a maximum amount of heat loss occurs from open water. On the other hand, minimum ice formation occurs if there is a small halocline at a depth of a few meters and if mixing is weak or absent early in the cooling season. In this case, an insulating layer of ice, perhaps reinforced by snow, forms early while there is still substantial heat content in the water beneath. As the ice grows, the expelled salt eventually eliminates the shallow halocline with the resulting convection bringing the heat from deeper water up to the ice, thereby inhibiting its growth. In the case of maximum ice formation, substantial heat is available early in the cooling season, the amount diminishing as the ice grows rapidly. With minimum ice formation, less heat is available and it is much more uniformly distributed throughout the cooling season.

Thin Ice and Thick Ice

Let us compare the two situations in early summer. Any ridging, or rafting of ice reduces the total surface occupied by ice and increases the area of open water. The surface of the water has a very low albedo, while the ice has a high one; during the melting season, the more open water produced, the more solar energy absorbed. The wind stress on the surface of the ice is not generally linked to its thickness. However, the ability of the ice to resist this stress without ridging or rafting increases with thickness. Therefore thin ice generally absorbs more heat than thick ice. And of course with thin ice there is less ice to melt. All other things being equal, thin ice regions become ice-free, or of low ice concentration, earlier in the melting season than do thick ice regions. Their overall summer albedo is much lower, and they gain more energy from the sun, becoming warmer at the end of the heating season. Thus rather small differences in ocean mixing early in a cooling season can have effects lasting a year or longer.

There is another possible scenario. When the water depth, or the depth of the halocline, is great, open water may persist throughout the cooling season. In this case, a maximum amount of solar energy is absorbed in the heating season because there is no high albedo ice surface. The heat thus gained can act as a storage source for the large winter heat loss. This appears to be the case in the northwest Norwegian Sea. There has been speculation that if the Arctic were divested of its ice cover, it might behave similarly — particularly if river diversions reduced the inflow of fresh water. At present, the Arctic is in a state comparable to maximum ice formation. There is a layer of low-salinity water near the surface that is abundant enough so that salt expulsion by freezing is unable to increase the density to the point where it would become heavier than the underlying warmer water. This configuration encourages ice formation.

Perhaps more important than strictly one-dimensional variations in ice cover are those caused by advection. It is generally taught in introductory oceanography courses that drifting pack ice responds to wind, while icebergs respond mainly to ocean currents. In fact, pack ice and icebergs are influenced by both wind and current, although icebergs are appreciably less affected by wind than is pack ice. Observations (M. G. McPhee, 1978) indicate that the drag coefficient between ice and water is about twice that between the atmosphere and the ice. This implies that, under a steady wind, the ice would move at about 2½ percent of the wind speed relative to the water some meters deep. Classically, the ice moves at an angle to the right of the wind stress (in the Northern Hemisphere). The angle has a large scatter, with data indicating something like 20 degrees ± 15. At typical wind speeds, the ice drifts a couple of points to the right of the wind with a speed of 10 to 30 centimeters per second relative to the water. This is higher than most current speeds, but not so much so that the current can be ignored. Where there are strong boundary currents, such as off the east coast of Greenland, transport by current is far from negligible in comparison to that by wind.

The Boundary Between Ice and Water

The location of a boundary between sea ice and open water unconfined by continents is determined by a combination of current, wind drift, freezing,

Figure 4. Skylab near-vertical photograph of the northeastern coast of Hokkaido, Japan, on January 21, 1974, showing the consolidated pack ice off Abashiri. Ice plumes as long as 50 kilometers are visible off the coast, and large ice eddies occur in the pack between Abashiri and Esashi. (Source: Campbell, and others, 1977)

and thawing. The latter two depend on radiation, including the effects of cloudiness, the temperature and mixing regimes in the upper ocean, and heat exchange with the atmosphere, which in turn depends mostly on the vagaries of weather. Formulating a useful model for determining the location of the ice boundary is no simple task; in fact, the problem has not been solved. Indeed, under many circumstances, the sea ice boundary is even difficult to define. Satellite photographs frequently show ice plumes and eddies, as illustrated in Figure 4. The nature and scale of these features make it almost certain that they are associated with ocean current patterns.

There are large interannual variations in the amount and location of ice cover. Figure 5, from W. J. Campbell and others, shows the cover that existed in the Sea of Okhotsk and the Bering Sea in early February for each of the years 1973 through 1976. Much has been written about the effect of sea-surface temperature (SST) anomalies on the atmosphere (see page 27). SST anomalies rarely exceed 2 degrees Celsius. The surface temperature "anomaly" associated with a sea ice anomaly can reach 40 degrees!

Ice can sustain very substantial compressive stress. Pressure applied in one area by wind or current can be transmitted through the ice for very large distances, and results in movement far from the location where it is applied. Under certain circumstances, this can influence the location of the ice boundary.

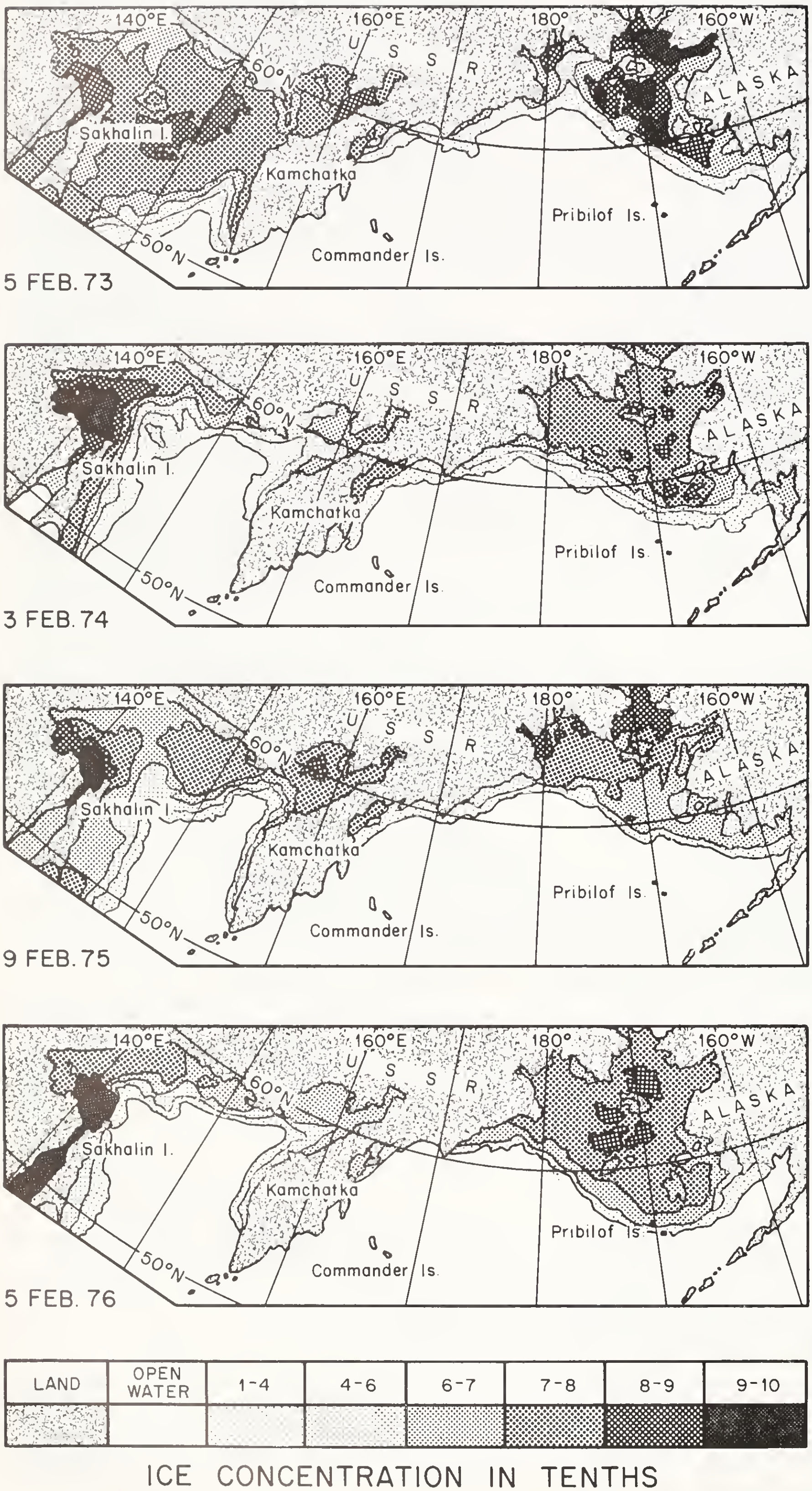


Figure 5. Interannual variation of sea ice cover in the Sea of Okhotsk and the Bering Sea. (After Campbell and others, 1978)

The dense ice pack of the Arctic has received considerable study in recent years, particularly within the framework of the Arctic Ice Dynamics Joint Experiment (AIDJEX). A principal object of AIDJEX has been to determine the large scale rheology* of floating sea ice. In the AIDJEX model (M. D. Coon, and others, 1974), pack ice is treated as an elastic-hardening plastic material. A somewhat different model has been proposed by J. R. Marko and R. E. Thomson (1977); they emphasize the semi-brittle failure of pack ice, drawing an analogy with rock mechanics. It is hoped that the information gained during the first global experiment of the Global Atmospheric Research Program (GARP) in 1978-79 will help clarify the picture of ice movement under stress. A number of satellite-reporting ice buoys will be scattered over the Arctic Ocean and their positions tracked. Since this will be a year in which the atmosphere is intensively studied, it is hoped that unusually good atmospheric stress fields will be available to test existing models and formulate new ones.

It is becoming clearer that even in winter the Arctic Ocean is not completely covered with ice. P. Gloersen and co-workers, using passive microwave information gained from satellites this year, have been able to show that substantial compression and expansion movements occur in the central Arctic as late as mid-January. Such movements are important both dynamically and thermodynamically. The rheology of an expanded region will be quite different from that of a compacted one, and any model describing pack ice movement in detail will have to account for this difference. Thermodynamically, an expansion is important because it must (at least temporarily) create regions of open water. The measurements which exist indicate that small areas of open water transmit up to 100 times more heat through the surface than do equal areas of ice, so that thermodynamically even 1 percent of open water is very important. And there is at least that much open water even in the high Arctic winter, according to observations. Even after these open-water regions have frozen, the resulting thin ice transmits much more heat than the thicker surrounding ice.

When the open water area is large, the air mass transformation above it leads to a lower heat transfer per unit area. Although one can be confident of such a statement on theoretical grounds, there are few observations to support it. Quite large areas of open water — polynyas — do occur in certain areas. Ultimately, we need to know much more about them.

To this point, the concentration has been upon the Arctic, not because it is more important but because we have more information on the behavior of Arctic ice than on that of Antarctic ice. In fact, there has been very little research done on the surface of Antarctic pack ice. We are beginning, however, to get valuable information from satellites, showing that Antarctic ice cover has very substantial inter-annual variations (Figure 6). These data also reveal that the ice cover is not continuous, and that polynyas occur well within the outer limits of the pack ice even in winter. It is probable that variations in the Antarctic winter ice pack are at least as important to climate as are those in the Arctic — perhaps more so. The area of sea ice that grows each winter in the Antarctic is equivalent to that of the entire Antarctic continent, and covers more than 10 percent of the ocean area of the Southern Hemisphere. Unlike the Arctic, the outer boundary of the sea ice is not constrained by continents. It is thus very mobile.

It will be necessary to conduct a great deal of research on Antarctic sea ice if its behavior is to be modeled satisfactorily. While the Arctic experience will have some relevance, it cannot be transferred

Recently fractured cake ice in Antarctic. (Photo A. W. Erickson)

Major fissure in Ross ice shelf. (Photo A. W. Erickson)

*Science dealing with the deformation and flow of matter.

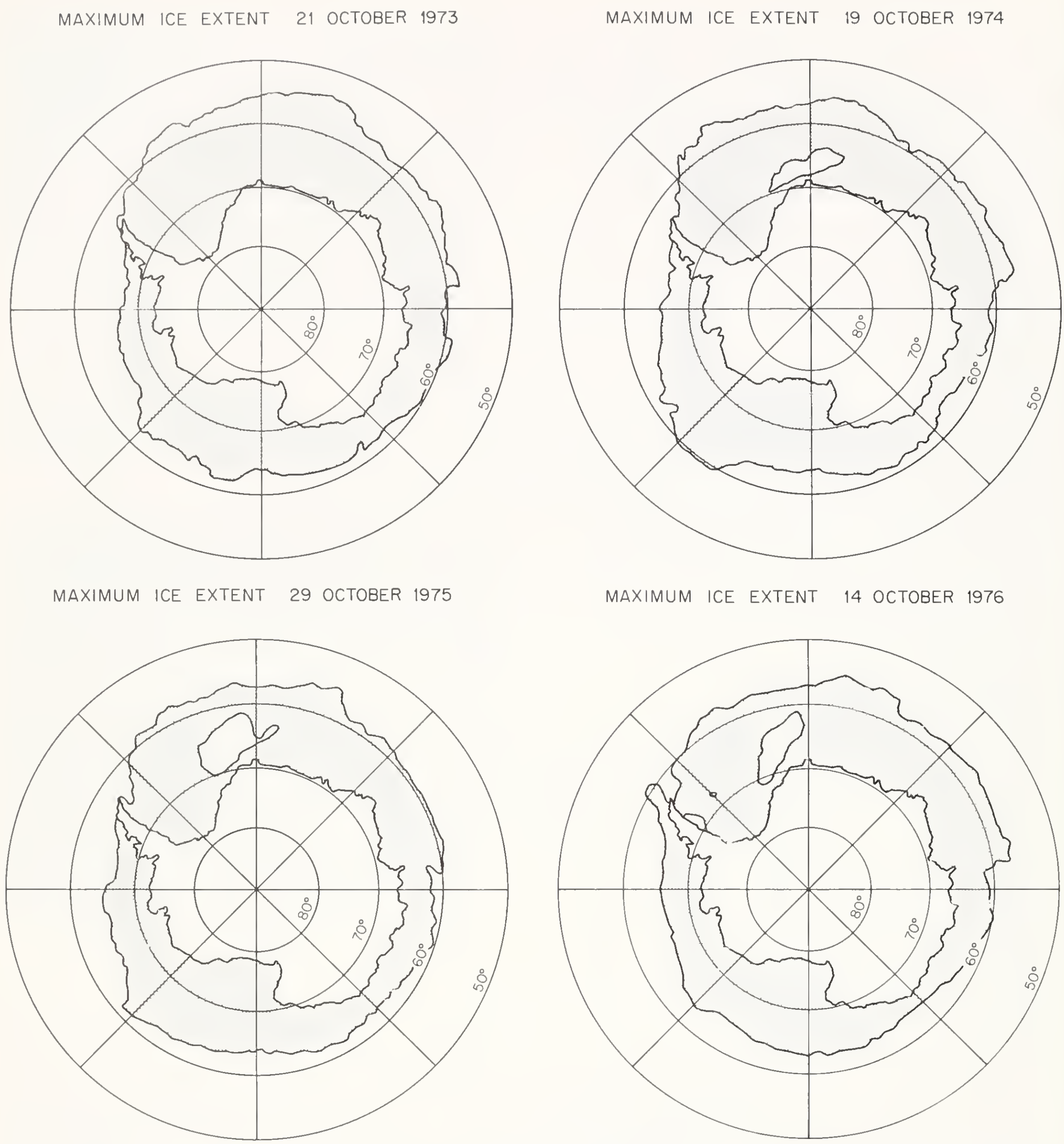


Figure 6. Interannual variation of the maximum sea ice cover around the Antarctic continent. Note the large polynya that existed in the eastern Weddell Sea in 1974, '75, and '76, but not in 1973. (Source: R. O. Ramseier and H. J. Zwally, 1978, personal communication)

without modification. Virtually all of the sea ice — as opposed to icebergs of terrestrial origin — in Antarctic waters is annual ice, disappearing each summer. In contrast, according to Vowinckel and Orvig (1970), more than 88 percent of central Arctic ice is at least two years old, and more than 60 percent is older than five years. The difference is important. Not only is multi-year ice thicker, particularly in the first few months of the cooling season, but it contains much less salt and is therefore substantially harder than one-year ice. Thus it can withstand more compressive stress than one-year ice, without ridging.

Clearly, compression and expansion are important to the behavior of sea ice. Unfortunately, they also are complicated to model. Even if one neglects the effects of ocean currents, which are even less well understood under ice than they are in the open ocean, the response to wind stress is extremely complicated. As was pointed out previously, uncompacted ice drifts at an angle that is not very well determined, but which has a mean value of about 20 degrees from the direction of wind stress. This means that compression is determined

not only by the oceanographer's old friend the wind stress curl but even more importantly by the wind stress divergence. If the ice moves in the direction of the wind stress, the wind stress curl merely causes it to rotate, while the wind stress divergence causes it to spread out (or compact if the divergence is negative). Since the ice moves at an angle from the stress, the curl of the stress causes some compaction and the divergence some rotation. As the ice becomes compacted, and moves less freely with respect to the water, it is to be expected that wind stress curl will become decreasingly important relative to wind stress divergence.

Although we know a good deal about sea ice, there are still gaps in our knowledge. With the help of satellites, we can now get good descriptions of sea ice cover. By close examination of the atmosphere, we should be able to learn something of the effects of changes in sea ice cover on atmospheric behavior. Through observation and calculation, we also can improve our ability to model the behavior of the sea ice.

The Road Ahead

This article has focussed frequently on modeling. The reason for this is the nature of climate study. Apart from the intellectual interest in trying to describe and understand past climate changes, the principal functions of climate study are to determine the probable nature of future climate changes and to determine the sensitivity of the climate system to exterior changes, such as the increase in the amount of carbon dioxide in the atmosphere (see page 12).

Although some things can be done by careful and intelligent interpretation of observations, it is generally agreed that much of the information we need will only be attainable with the assistance of models. The various interactions involved in determining climate are so complex that it seems difficult to handle the problem in any other way. To use the sea ice problem as an example: ice cover depends in part on the radiation balance, which is significantly influenced by cloudiness, which depends in part upon the atmospheric moisture content, which in turn depends in part upon the ice cover. And the movement of ice depends in part upon ocean currents, which are in large part determined by wind stress on the water; and, in the neighborhood of ice, the stress is modified by the presence of the ice.

Complex feedbacks of this kind are very difficult to deal with unless one constructs models. On the other hand, the models will be reliable only if they are supported by observations. There are few instances where our theoretical understanding is sufficient enough to generate the necessary parameters for the models.

It seems certain that a relatively complete understanding of our climate system cannot be achieved without including the behavior of sea ice. As is the case in many other facets of climate study, we have some way to go with respect to observations and modeling.

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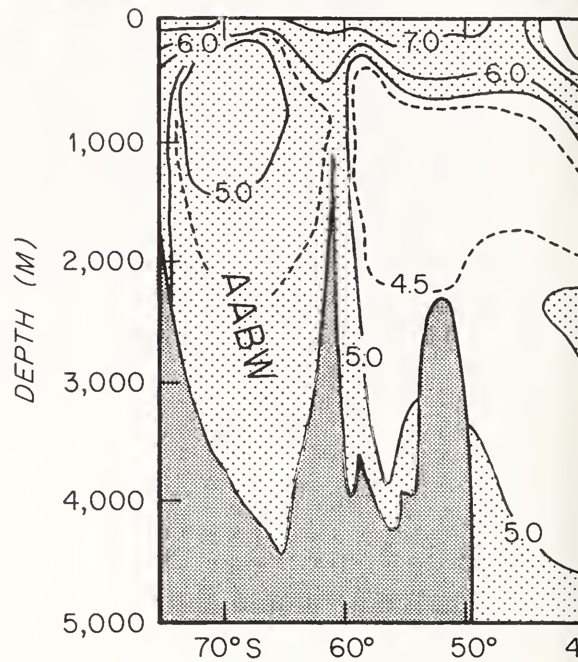
Response of the Deep Sea



by G. P. Lohmann

Ice ages have been a regular, recurring feature of the earth's environment for nearly two million years. Their expression in terrestrial and sea-surface climate has been documented in great detail. We know, for example, that both the land and the surface of the sea have responded directly and in parallel to the growth and retreat of high-latitude ice caps. We know very little, however, about how these ice ages have affected the deep ocean.

Most deep and bottom waters are formed today in high latitudes, when warm surface waters flow into polar seas, become cooler and consequently more dense, and sink (Figure 1). Because this process occurs in high-latitude areas, areas that are covered with ice or otherwise strongly affected by ice age climate, it is clear that deep-ocean circulation must be very sensitive to such extreme changes in climate.

Two Views of Deep-Ocean Circulation

In 1968, Val Worthington of the Woods Hole Oceanographic Institution and Peter Weyl of the State University of New York at Stony Brook each put forth hypotheses on the deep circulation of an ice-age ocean. In Worthington's view, glacial deep-ocean circulation was similar to today's, but the density of glacial deep and bottom waters was somewhat greater, primarily as a result of an ice-age ocean's higher salinity. It is calculated that the average salinity of the world's oceans increases by 1 part per thousand (from 34.7 to 35.7 ‰) during ice ages as fresh water is trapped in glacial ice caps. Assuming that all other factors underlying deep-water formation remained unchanged, Worthington showed that the density of glacial bottom waters would have been much greater than the density of any water now existing in the deep ocean. The most dramatic effect that formation of this kind would have on deep-ocean circulation occurs during deglaciation — the time that an ice age ends and polar ice caps melt. According to Worthington, the oceans were stably stratified for a short time, with very dense glacial bottom water filling deep-ocean basins and relatively fresh, light glacial melt waters at the surface. Under these circumstances, high-latitude production of deep and bottom waters did not occur, at least not by present mechanisms, and deglaciation led to near stagnation of the world's deep ocean. Worthington calculated that this situation lasted up to 15,000 years, or as long as it took for geothermal heating from below and mixing from above to remove the dense glacial water from the deep-ocean basins.

Weyl's hypothesis differed in several respects from that suggested by Worthington. The fundamental difference was that he emphasized the special sensitivity of the world oceans' deep circulation to changes in climate at high latitudes. In his view, the present-day sources of deep and bottom waters — the shallow polar seas — could not have existed during ice ages, because they were covered by glacial ice. As production of cold, dense waters in these areas decreased, waters elsewhere of lesser density were allowed to sink. With access to the cold polar seas restricted by ice cover, the densest surface waters available (and therefore the best candidate as a new source of deep water) were the warm, but salty, waters of the central North Atlantic. In Weyl's view, glacial deep and bottom waters were formed from these warm, salty waters in the open ocean, not of water cooled in the

to Ice Ages

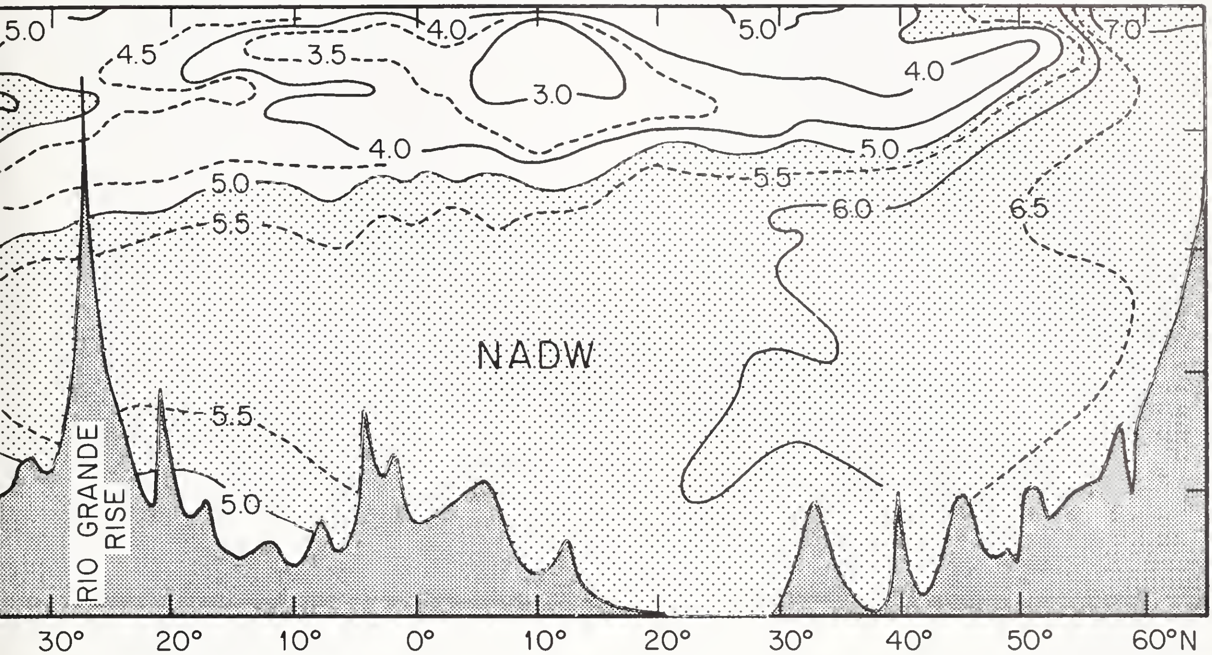


Figure 1. Cross-section of the western Atlantic Ocean, showing the distribution of oxygen in the deep sea (milliliters per liter). Regions of high oxygen delineate newly formed deep and bottom waters such as the North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW). These water masses are formed of oxygen-rich surface waters that are cooled in polar seas, sink, and spread through the deep Atlantic. (After Sverdrup, and others, 1942.)

shallow polar seas as is the case today. As with all deep waters, the character of this glacial deep water reflected its source, so Weyl's glacial deep ocean was both saltier and several degrees warmer than today's (Figure 2).

Although an oversimplification, we can summarize these two hypotheses as follows: Worthington's view is that an ice age will lead to formation of glacial bottom water denser than any that exists in the modern ocean; Weyl's idea is that an ice age may actually warm the deep water as polar seas freeze, formation of cold bottom water stops, and warm, salty waters of the central North Atlantic sink and fill the ocean basins.

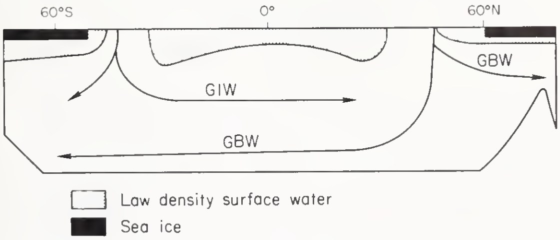


Figure 2. Hypothetical deep circulation of the Atlantic Ocean during an ice age as envisioned in 1968 by Peter Weyl. Although Glacial Intermediate Water (GIW) is similar to today's, Glacial Bottom Water (GBW) is formed in the central North Atlantic and is, therefore, both warmer and saltier than modern bottom water. The present sources of deep and bottom water, the shallow polar seas, are covered by sea ice.

History of Deep Ocean Reconstructed

The major problem with evaluating and choosing between these views has been the lack of a documented history of how the deep ocean circulated during an ice age. One study attempting to provide such evidence was recently undertaken by this author at the Woods Hole Oceanographic Institution. Its primary objective was to reconstruct a detailed history of the deep ocean over the last several hundred thousand years, in terms that would determine its response to ice ages.

The study focussed on an area in the western South Atlantic where a large submarine ridge, the Rio Grande Rise, extends to a height of more than 4,000 meters above the surrounding sea floor, with most of the major Atlantic deep-water masses impinging on its flanks. This feature is shown in Figure 1. It presents a situation that is especially useful for the study of past deep circulation, because it allows us to characterize the present-day

pattern of deep-ocean circulation in terms of the effects that it has on the sea floor. Once this imprint is recognized, it can be used as a key to understanding the record of past changes in deep circulation that is preserved in deep-sea sediments.

Perhaps the clearest relationship we see in the modern oceans between deep oceanography and sea-floor sediments is the systematic decrease in the water column of the calcium carbonate content with increasing water depth. In the open ocean there is a constant rain from surface waters to the sea floor of dead planktonic marine organisms in the form of tiny calcareous shells that contain calcium carbonate. Although most of these particles reach the sea floor, most are not preserved in deep-sea sediments because they tend to dissolve, with the deepest, coldest bottom waters being especially corrosive (Figure 3).

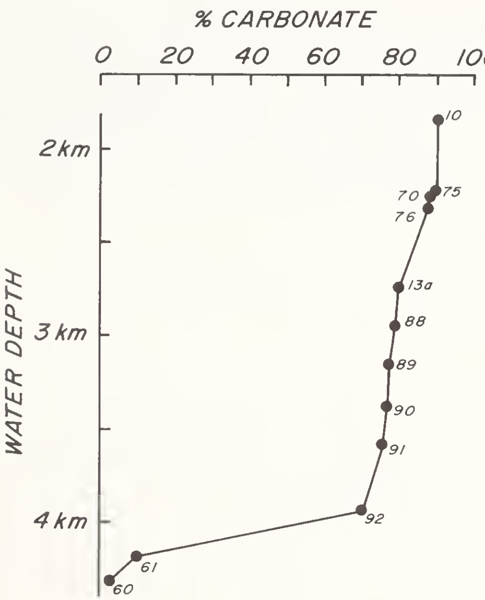


Figure 3. Carbonate content of sediments recovered from the west flank of the Rio Grande Rise. Transition from NADW to AABW coincides with the sharp drop in carbonate content at 4 kilometers.

In the South Atlantic, the deepest, coldest, and most corrosive water is the northward-flowing Antarctic Bottom Water (AABW). The transition from the overlying, southward-flowing North Atlantic Deep Water (NADW), which is warmer and less corrosive to calcium carbonate, to the underlying AABW is characterized by a very sharp drop in the carbonate content of the sediments that are in contact with these water masses. This sharp increase in carbonate dissolution coincides with the transition between NADW and AABW throughout much of the Atlantic Ocean and presents us with one possibility for reconstructing past changes in deep-ocean circulation.

A number of deep-sea sediment cores were recovered in 1971 and 1974 from the western flank of the Rio Grande Rise during cruises of the Woods Hole Oceanographic Institution's research vessels *Atlantis II* and *Chain*. The average carbonate content of these cores is plotted in Figure 3; the sharp drop in carbonate content (reflecting the sharp increase in carbonate dissolution) occurs at about 4,100 meters, the depth of the transition between NADW and AABW. If this transition of water masses has always been characterized by a sharp change in the sediment carbonate content, then we should be able to monitor changes in the level between NADW and AABW through time by studying changes in the carbonate content of deep-sea sediment cores taken in the vicinity of the transition.

It is possible to estimate the age of sediments recovered in deep-sea cores using a variety of techniques. We know, for example, that Core 88, which is a sediment column about 700 centimeters long, represents a continuous record of sedimentation from approximately the last 700,000 years. On average, sediments in this core have accumulated at a rate of a fraction less than a centimeter for each 1,000 years. Since a glacial/interglacial climate cycle typically lasts about 100,000 years, the sediments in Core 88 record variations in carbonate content through the last several glacial-interglacial cycles.

Figure 4 shows the variations through time in carbonate content of sediments in Core 88. Also shown are variations in the oxygen isotopic composition of some microplankton shells preserved in these sediments. Changes in the proportion of the two different isotopes of oxygen in these shells is primarily a result of changes in the volume of the polar ice caps. Oxygen-16, the lighter isotope, evaporates more readily from the sea surface and accumulates preferentially in ice; the heavier isotope, oxygen-18, remains in seawater, where it is incorporated into the shells of microplankton. Because of this natural fractionation of the oxygen isotopes between ice and seawater, the variations in isotopic ratios in Figure 4 are a record of past changes in the volume of the polar ice caps. Figure 4 also shows the variations in abundance of a certain species of microplankton, *Globorotalia truncatulinoides*, preserved in the Core 88 sediments. This species of foraminifera lives near the surface and, in the modern South Atlantic, is abundant in waters cooler than those now surrounding the Rio Grande Rise. The increases in abundance of *G. truncatulinoides* indicate times during the last 700,000 years when surface waters above the Rio Grand Rise were cooler than today's. In Core 88 (and in most of the sediment cores studied from the Rio Grand Rise),

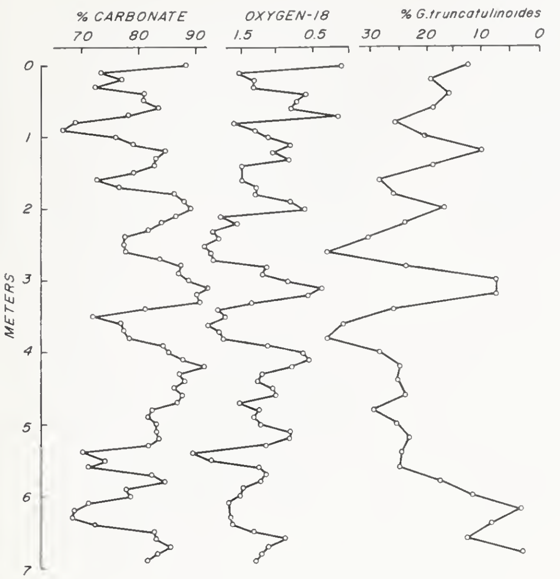


Figure 4. Past variation in sediment carbonate content, oxygen isotopic composition of planktonic foraminifera, and abundance of Globorotalia truncatulinoides *as recorded in Core 88. This deep-sea sediment core is one of several recovered from the Rio Grande Rise during cruise 115 of the* R/V Chain. *The proportion of oxygen-18 increases when the volume of the ice caps in the Northern Hemisphere increases; the last eight ice ages are recorded in Core 88. Increased abundances of* G. truncatulinoides *indicate cooling of the surface waters overlying the Rio Grande Rise.*

the changes in sediment carbonate content, the changes in ice volume indicated by oxygen isotopes, and the changes in abundance of *G. truncatulinoides* are all parallel. We see that the carbonate content of the sediments is lowest when polar ice volume is greatest and local sea-surface temperatures are coolest. If we attribute the changes in carbonate content to changes in the level between NADW and AABW, then these carbonate minima should indicate times of increased volume of AABW, which occurred during ice ages.

This conclusion contradicts the model of glacial deep circulation proposed by Weyl. As you recall, he theorized that the sources of cold bottom water production were frozen over during ice ages, thus decreasing the amount formed as well as causing deep and bottom waters to become warmer and, therefore, less corrosive to calcium carbonate. If that was the situation, we might expect more carbonate in sediments deposited during ice ages, not less. The changes in carbonate content of sediments from the flanks of the Rio Grande Rise provide evidence that the response of the deep sea to ice-age climate has been to increase the volume of cold, corrosive bottom water in the ocean basins.

Unfortunately, it has been found that the causes of past variation in the carbonate content of sediments are not as straightforward as I have assumed in this discussion. It has been shown that, in some parts of the ocean, the decrease in carbonate during ice ages is caused by noncarbonate, continental detritus being washed or blown into the deep sea rather than by increased dissolution of carbonate by corrosive bottom waters. And in other areas, the amount of carbonate preserved in deep-sea sediments actually increased during ice ages, apparently the result of large increases in the local production of microplankton with calcareous shells. For these reasons, the variation in carbonate content of sediments seen in all cores recovered from the Rio Grande Rise, including ones well above any possible influence of AABW, might easily represent changes in something other than deep-ocean circulation. All we are certain of is that changes in deep-sea sediment carbonate in the western South Atlantic almost exactly parallel the changes in surface climate indicated by oxygen isotopes and by temperature-sensitive plankton. Because of the ambiguities in the carbonate record, however, another criterion was developed for recognizing past changes in deep circulation — one that appears to be more sensitive to changes in the deep-sea environment. It is based on the fossils of microorganisms that once lived on the bottom.

Reconstructing the surface of the ocean during ice ages was made easier when it was recognized that surface water masses could be characterized by certain species of microplankton that reflect the sea-surface environment and that are preserved in deep-sea sediments. Similarly, the deep-water masses of the South Atlantic also could be associated with distinctive species of deep-living microorganisms. At each point where the major deep-water masses of the South Atlantic Ocean impinge on a flank of the Rio Grande Rise, there is an associated characteristic benthic foraminiferal fauna. One of the most striking associations is between *Epistominella umbonifera* and the AABW.

E. umbonifera is a major constituent of the abyssal microbenthos in much of the world's oceans. It is one of many benthic foraminifera that forms a calcitic shell (Figure 5), and is generally preserved in deep-sea sediments. In the western South Atlantic, *E. umbonifera* characterizes an assemblage of benthic foraminifera that systematically becomes more numerous in deeper water, reaching its greatest abundance in sediments beneath the AABW (Figure 6). Although the ecology of this species is not known, variations in its abundance are strongly correlated with many of the physical and chemical properties of seawater that identify AABW. To the extent that these correlations existed in the past, the fossil record of *E. umbonifera* and its associated species of benthic

Figure 5. Scanning electron micrographs of several species of benthic foraminifera that presently live on the sea floor around the Rio Grande Rise. Pyrgo *(1-2) and* Planulina wuellerstorfi *(5-6) are associated with the North Atlantic Deep Water;* Uvigerina peregrina *(3) and* Globocassidulina subglobosa *(4), both widespread in the deep Pacific Ocean, occur on the Rio Grande Rise beneath the Circumpolar Deep Water, a water mass that originates in the Pacific, then flows into the western South Atlantic; and* Epistominella umbonifera *(7-9) predominates in sediments that lie beneath the Antarctic Bottom Water. Magnification 50x.*

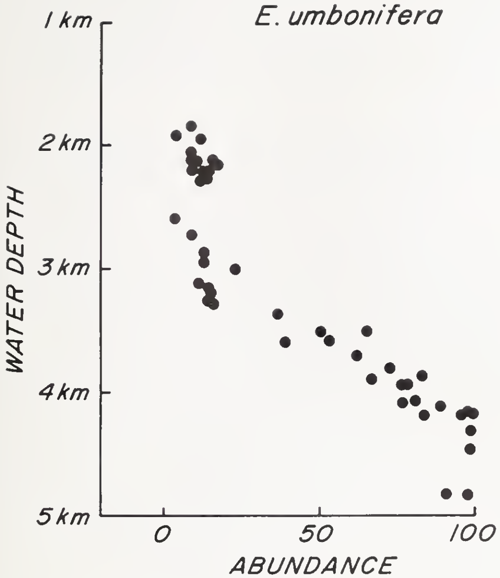


Figure 6. Abundance of the benthic foraminiferan species, Epistominella umbonifera, *on the flanks of the Rio Grande Rise. The maximum abundance of this species is greatest in sediments that are in contact with the Antarctic Bottom Water; the upper limit of AABW today is at 4 kilometers water depth.*

foraminifera can be used as an indicator of past changes in the AABW.

The assemblage characterized by *E. umbonifera* is common in all of the deeper cores studied in the South Atlantic. And the abundance of these benthic foraminifera has changed markedly in these cores through time. These changes, as they appear in the 12 deep-sea cores from the west flank of the Rio Grande Rise, are shown in Figure 7. The cores were recovered from water depths of between 1,800 and 4,200 meters, and the five deepest cores were taken around the transition from NADW to AABW. As expected, this transition is where the greatest changes in abundance of *E. umbonifera* through time are seen. By comparing the timing of these changes with the changes in climate recorded in the same cores, we can see how the deep circulation of at least this part of the ocean was altered by the ice ages.

An average of the variations in abundance of *E. umbonifera* from the five longest deep-sea cores is shown in Figure 8. If this species of benthic foraminifera has always preferred living beneath the AABW, then these variations reflect rising and falling of the level between the NADW and AABW, and we can determine whether or not the volume of AABW has changed through time, particularly during the last several ice ages. The result is surprising.

No Consistent Response

Unlike the surface ocean, the circulation of the deep sea does not reflect, at least not in a simple way, the periodic changes that characterize world climate of the last several hundred thousand years. And there has been no consistent response of the deep sea to an ice age. If increased abundances of *E. umbonifera* are any indication, the amount of AABW in the western South Atlantic has frequently increased during ice ages. Either the areas in which it is formed do not freeze over, or, if they do, ice age AABW is formed elsewhere. It is apparently indistinguishable from modern AABW, at least to *E. umbonifera,* and it is formed in greater quantity. This result suggests that the pattern of deep circulation envisioned by Worthington may have developed during some ice ages, but it is not an invariable response.

During some ice ages, specifically the ones 270,000 and 660,000 years ago, the amount of AABW flowing through the western Atlantic decreased. In fact, the particularly low abundances of *E. umbonifera* seen in deep-sea cores at those times indicate that there was less AABW then than at any other time during the last 700,000 years. During

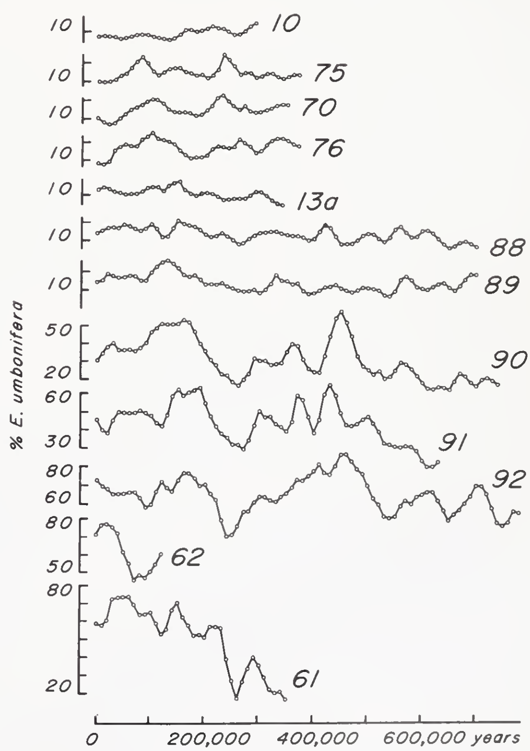
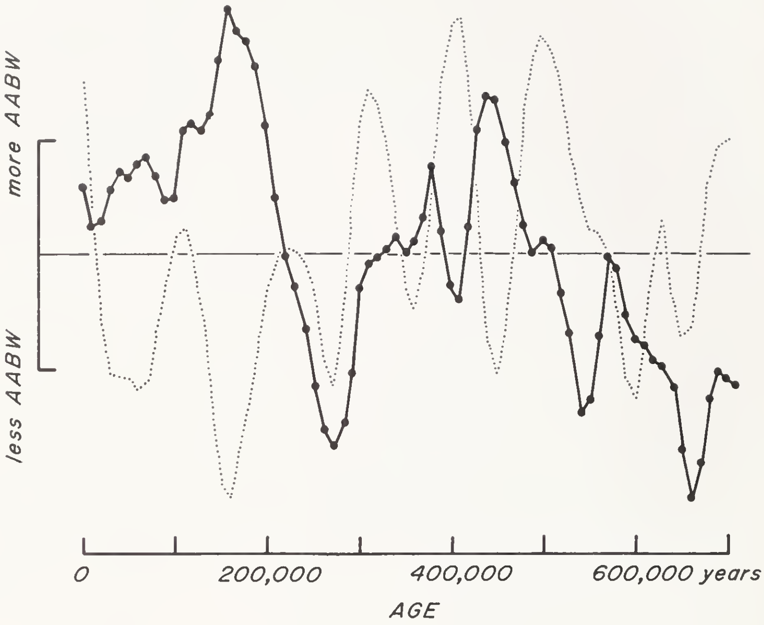


Figure 7. Variations in abundance of Epistominella umbonifera, *an indicator of the Antarctic Bottom Water, in sediment cores from the west flank of the Rio Grande Rise.*

Figure 8. Variation in the Antarctic Bottom Water (solid line) during the last 700,000 years compared with climate change (dotted line). The index of change in AABW is an average of the changes in abundance of Epistominella umbonifera *from Figure 7. The climate index is an average of changes in sediment carbonate content, which in the area of the Rio Grande Rise is known to parallel climate change. The carbonate minima correspond to times of ice age climate. The vertical scale is in units of standard deviation from the mean.*



these two ice ages, the pattern of deep-ocean circulation seems to have been as Weyl suggested. The formation of deep and bottom water by the mechanisms we see today did not occur, or at least *E. umbonifera* did not recognize any in the western South Atlantic.

At the present time our evidence for glacial deep circulation is very limited, but what we do have indicates that the response of the deep ocean to ice ages has been much more irregular than has been the response of the ocean's surface. I have presented some of the evidence which suggests that the increased production of cold bottom water envisioned by Worthington and the decreased production envisioned by Weyl have both occurred during ice ages. It is not clear, however, why some ice ages have produced the one pattern, and some the other.

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Geological Perspectives on our Changing Climate

by John Imbrie

Sooner or later, every scientist studying past climates is asked if our atmosphere has been warming up or cooling down. Posed in this way, the question is unanswerable: the proper response depends entirely on the interval of time being considered. For example, if atmospheric temperatures are averaged over single years, and then compared with averages for the preceding two years, the resulting pattern of between-year variations forms a series that is almost random. Almost, but not quite. For careful statistical analysis has shown that there is a slight tendency for the average temperature during any year to be similar to temperature averages calculated over the previous one or two years. This tendency, called *quasi-biennial oscillation*, has not been satisfactorily explained. But many scientists look for an explanation in terms of interactions between the rapidly-responding atmosphere and the thermally-sluggish ocean.

If the year-to-year variability is ignored (or averaged out), and the time scale of interest expanded to include several decades, some atmospheric records show clear-cut trends. Two trends of this type — first documented convincingly by J. M. Mitchell, Jr. of the National Oceanic and

(Photo by Alexander Lowry, PR)

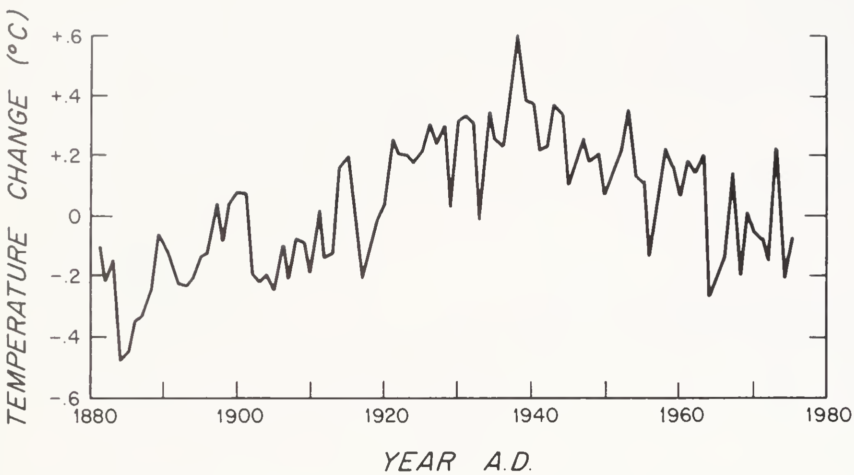

Figure 1. Climate of the last 100 years, showing changes in the average annual temperature of the Northern Hemisphere. Since 1938, average temperatures have declined about 0.6 degree Celsius. (From J. M. Mitchell, Jr., 1977a.)

Atmospheric Administration — are illustrated by the record of Northern Hemisphere air temperatures in Figure 1. Since 1938, for example, average temperatures have declined about 0.6 degree Celsius. Impressive as this trend is, bear in mind that the numbers plotted on this graph are hemispheric averages. Some stations, particularly those in low latitudes, show trends that are similar in direction but much smaller in amplitude than the average; other stations, particularly those in high latitudes, show declining trends that are considerably larger than the average. And many locations show no trend at all — or warming trends that run counter to the hemispheric average. Despite this complex spatial structure, there is no doubt that the 40-year cooling trend exhibited by the hemispheric average is real, and demands an explanation. Unfortunately, this phenomenon — like so many other characteristics of climate — is not fully understood.

Despite this uncertainty, some journalists and other writers — eager to dramatize a blizzard or draw attention to a prolonged cold snap — publish interpretations each winter based on the observed 40-year cooling trend. The logic of these prognostications is simple: having persisted for many decades, the trend can be expected to continue indefinitely, until the Earth enters another ice age. It is even possible to calculate when this new ice age will occur: given a 0.6 degree Celsius decline every 40 years, it would take 400 years to reach a temperature level characteristic of the last major ice age, some 6 degrees Celsius cooler than today.

However, before those readers of *Oceanus* who live in New England rush to put their homes up for sale and move to the Sunbelt, they should remember that making predictions based on trends of unknown origin is a risky business indeed — a principle that many investors in the stock market will confirm. In fact, many modern prophets of climatic doom have no more justification than the soothsayers of old, who, on observing a three-month cooling trend each autumn, built mid-winter bonfires to encourage the god of the sun.

The danger of making climatic predictions based solely on trends is easily illustrated by reference to Figure 1. A journalist living in the mid-1930s, for example, would have a clear 50-year warming trend on which to base a scare story about the coming Age of Heat.

Proxy Data

What does the record of climate look like if we choose to ignore the decade-to-decade variability and expand the time-scale to include many centuries? To find an answer, we can no longer turn to instrumental records, but must depend instead on evidence gleaned from old logbooks and diaries, or from geological and biological records. Such indirect records of ancient climate are commonly called proxy data.

Among the most interesting of such proxy records are those analyzed by the English meteorologist and historian Hubert H. Lamb. Delving into records left by farming communities over the last 1,000 years, he compiled an index of winter severity that can be calibrated over the past century against instrumental records. Figure 2 shows the result of his research in Eastern Europe. On this graph, the observed severity index has been averaged over 50-year intervals and calibrated in degrees Celsius. Perhaps the most striking feature of this record is the Little Ice Age — a 400-year interval from about 1450 A.D. to 1850 A.D., when climates in Europe (and elsewhere) were markedly colder than they are today, and considerably colder than they were in the late Middle Ages. Several independent lines of evidence have confirmed this concept, and made it clear that over much of the

world Little Ice Age temperatures averaged a degree or two colder than they are today. Moreover, in the Alps, Scandinavia, Alaska, and New Zealand, valley glaciers were considerably extended beyond their present limits. We are therefore justified in viewing Hans Brinker, skating on Dutch canals that are usually unfrozen today, as a fictional representation of a real climatic event.

What caused the Little Ice Age? We do not know. One intriguing theory that is now being actively investigated links this event to a period of low solar activity known as the Maunder Minimum — an interval of time during which sunspots were notably rare. However, since there is no evidence that sunspot frequency is correlated with solar luminosity, the mechanism for the postulated solar-climate relationship is unknown.

If we expand our perspective to include proxy records of the last 10,000 years, paying particular attention to the geological records of mountain glaciation compiled by George Denton of the University of Maine and Wibjörn Karlén of the University of Stockholm, some interesting questions emerge. For in mountain ranges all over the world, glacial advances similar to those that characterized the Little Ice Age have occurred not once but several times. Moreover, according to a hypothesis advanced by Denton and Karlén, there is a notable tendency for these little ice ages to recur after an interval of 2,000 or 3,000 years. Whether this cycle is real or imaginary, and what causal mechanism might lie behind such a tendency, are unanswered questions. However, if this cycle is real, the geological forecast of the next 1,000 or so years — ignoring all of the higher-frequency fluctuations that would certainly be superimposed on such a cycle — would be a continuation of the present warm-climate regime.

If our chronological perspective is expanded once again, this time to include the last 500,000 years, we enter a realm of inquiry where the most continuous records of past climate are those that lie entombed in the muds of the ocean floor. As these muds accumulate, they incorporate the shells and other mineralized parts of many surface-dwelling and some bottom-living organisms. By analyzing these micro-fossils with proper taxonomic, chemical, and isotopic techniques, it is possible to decipher the record of past climate in some detail. The article in this issue by G. P. Lohmann (see page 58) summarizes some of the information that can be acquired by investigating the species composition of communities of bottom-living foraminifera. I will now summarize some of the climatic information that can be obtained by studying another aspect of the deep-sea record — the isotopic composition of the shells of planktonic foraminifera.

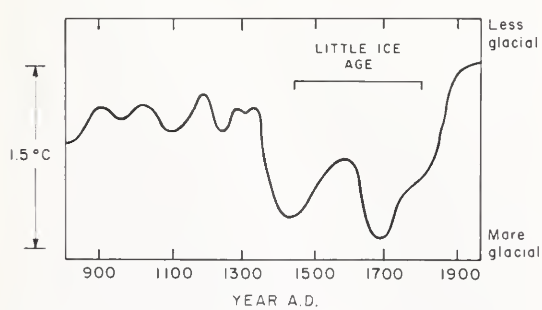

Figure 2. Climate of the last 1,000 years. The graph is an estimate of winter conditions in Eastern Europe as compiled from manuscript records. During the Little Ice Age (1450-1850 A.D.), mountain glaciers all over the world advanced considerably beyond their present limits. (Adapted from H. H. Lamb, 1966, by Imbrie and Imbrie, 1979. Used with permission.)

The Sediment Record

Early in 1971, as part of the National Science Foundation's International Decade of Ocean Exploration program, a group of scientists from different institutions joined together in the CLIMAP project to conduct an intensive investigation of climatic history as recorded in deep-sea piston cores. As part of this effort, James D. Hays of the Lamont-Doherty Geological Observatory at Columbia University selected two cores from the southern Indian Ocean for detailed study. Some of the results of this work are shown in Figure 3. Data plotted on this graph are isotopic measurements made by Nicholas Shackleton of Cambridge University, England, at intervals of 3,000 years over a sediment record that spans most of the last 500,000 years.

The curve shown in Figure 3 reflects changes in the ratio of two isotopes of oxygen as measured in the shells of the planktonic species, *Globigerina bulloides*. This method of studying climatic history was developed in 1947 by the Nobel laureate Harold Urey, then of the University of Chicago, and was first applied in 1955 to deep-sea cores by Cesare Emiliani, also then of the University of Chicago (now of the University of Miami, Florida). For a time, it seemed that the isotopic method would be capable of monitoring changes in the temperature of the Pleistocene ocean (from 10,000 to approximately 2 million years ago). But in 1973, Shackleton and Neil Opdyke of Lamont-Doherty demonstrated that changes in the measured ratio primarily reflect the isotopic ratio of the seawater from which the foraminifera extract calcium carbonate. In turn, this ratio is controlled by the global volume of ice sheets. For as ice sheets grow, they accumulate the lighter isotope of oxygen (O^{16}) preferentially, leaving the ocean enriched in the heavier isotope (O^{18}). Conveniently for the geologist, mixing processes rapidly average out any local changes in isotopic composition and distribute them evenly

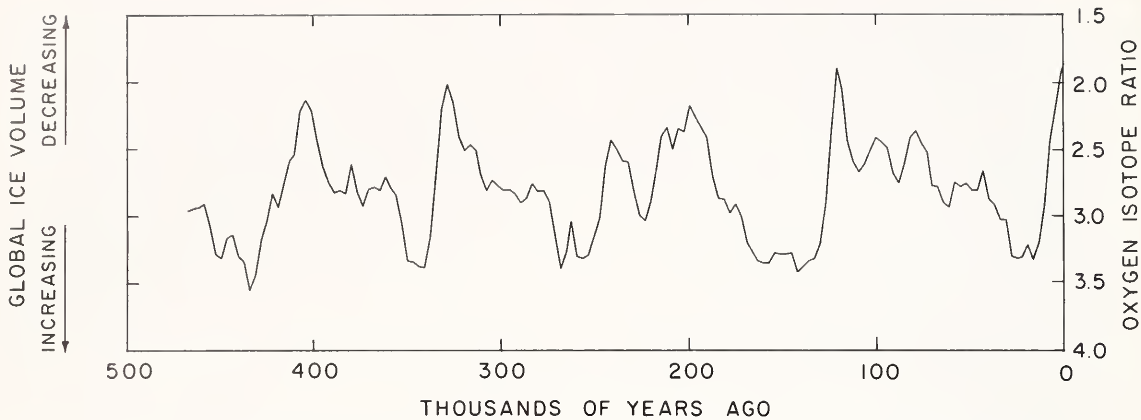

Figure 3. Climate of the last 500,000 years, showing the isotopic measurements made on two Indian Ocean cores by Hays, and others, 1976. These observations, which reflect variations in the volume of global ice, led to a confirmation of the astronomical theory of the ice ages. (From Imbrie and Imbrie, 1979. Used with permission.)

over all parts of the open ocean.

Thus the isotopic data plotted in Figure 3 (and similar data from other cores) are valuable as a *global* record of climatic change: they reveal how the total volume of the ice sheets has varied as a function of time. From independent geological evidence, it is clear that most of this variation is associated with the advances and retreats of the great Northern Hemisphere ice sheets. At their maximum extent, these ice sheets covered all of Canada, a substantial part of the northern United States, all of Scandinavia, most of Britain, and parts of Northern Europe and Siberia.

Because each of the points plotted on Figure 3 represents data that have been averaged over several thousand years, the graph provides no information about climatic fluctuations on the order of decades and centuries. However, the curve does make it clear that the succession of ice ages during the last 500,000 years is a periodic, or at least quasi-periodic, phenomenon. The dominant climatic cycle is on the order of 100,000 years. First identified by Wallace Broecker and Jan van Donk in 1970 (working at Lamont-Doherty), this cycle is dramatically expressed in a repetition of major glacial ages, such as those that occurred about 440,000, 350,000, 260,000, 130,000, and 20,000 years ago.

From a human perspective, the expression of this cycle in terms of a sequence of major *inter*glacial ages is even more interesting. The interglacial age in which we live — known as the Holocene Epoch — has lasted approximately 10,000 years. And the last interglacial, which peaked about 120,000 years ago, had a similar duration. Understandably, some optimists in the ski industry have been tempted to use these facts to forecast an early end of our present interglacial age, and the onset of another ice age. But such forecasts can have only a statistical, probabilistic basis. Like the forecasts of human longevity made by insurance companies, climatic predictions of this kind cannot tell when the life of any particular interglacial age will end.

Astronomical Theory of Ice Ages

What causes ice ages? Many theories have been proposed, but few are capable of being tested. One exception is the astronomical theory. In the form proposed by the Yugoslavian mathematician Milutin Milankovitch in 1924, this theory predicts what the frequency of ice ages should be. Thus it can be tested empirically by examining geological records of climate and finding out what the frequency of ice ages has actually been.

According to the Milankovitch theory, the succession of Pleistocene ice ages is caused by changes in the geometry of the earth's solar orbit. These changes, which can be calculated from a knowledge of the planetary masses and orbits, are shown in Figure 4. Two elements of the earth's orbit play the dominant roles in the astronomical theory: the *precession* of the equinoxes, which alters the earth-sun distance; and the *tilt* of the earth's axis relative to a perpendicular drawn to the plane of the ecliptic. Although changes also occur in the *eccentricity* of the earth's orbit, these variations were considered by Milankovitch to be important mainly because they determine the amplitude of the precession cycle.

Although these orbital variations have almost no effect on the total energy received by the earth each year, they do bring about changes in the seasonal and latitudinal distribution of that energy. Milankovitch calculated how much these changes would be, and concluded that they were sufficiently

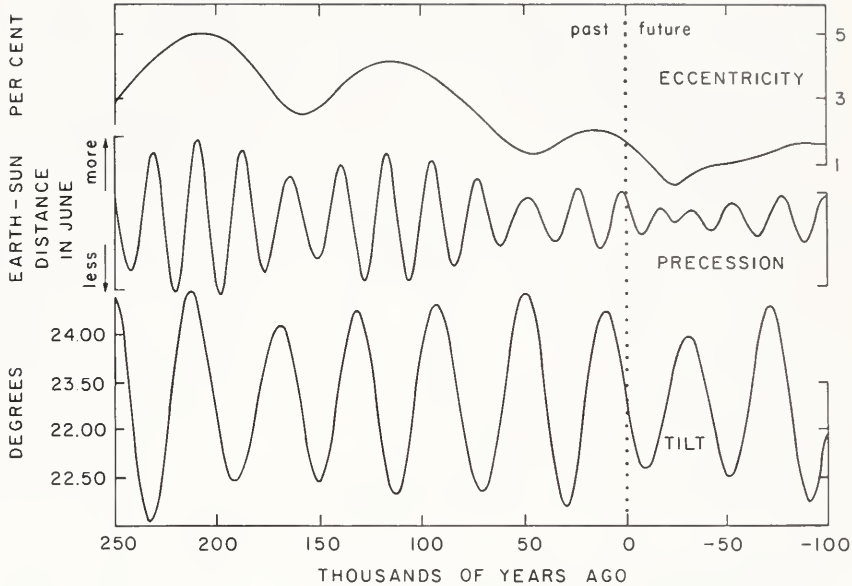

Figure 4. Changes in eccentricity, tilt, and precession as calculated by A. Berger, 1977. Planetary movements give rise to variations in the gravitational field, which in turn cause changes in the geometry of the Earth's orbit. These changes can be calculated for past and future times. (From Imbrie and Imbrie, 1979. Used with permission.)

large to cause the succession of ice ages and interglacial ages. If the Milankovitch theory is correct — and if the climate system responds in a simple (linear) fashion to these astronomically-induced changes in energy distribution — we can predict that the main climatic cycles should correspond to those of precession (19,000 and 23,000 years) and tilt (41,000 years).

Simple in principle, this test of the Milankovitch theory requires, first, that the chronology of the geological record of climate be reasonably accurate; and, second, that the record being studied be sufficiently detailed to preserve information at the frequencies of interest. After much struggle, the first of these requirements was finally met in the early 1970s, when the basic chronology of the marine record of climate was extended back about 700,000 years. This foundation was laid in two studies, one by Broecker and van Donk, and the other by Shackleton and Opdyke.

The second requirement was met in 1975, when Hays discovered two deep-sea cores from the Indian Ocean that had accumulated rapidly enough to allow analysis of isotopic fluctuations for a period as brief as 10,000 years. It was information derived from these cores, therefore, that was used in 1976 by Hays and his colleagues (Shackleton and this author) to conduct a test of the Milankovitch theory. This test consisted of analyzing the time series shown on Figure 3 (and two time series not shown) with statistical techniques capable of describing how the total observed climatic variance is distributed over various frequencies. The result is presented in Figure 5.

As predicted, significant concentrations of variance were found at or near cycles of 41,000, 23,000, and 19,000 years. Equally important, the climatic responses near 41,000 and 23,000 years were demonstrated to lag systematically behind the orbital curves. Believing that it was unlikely that these relationships resulted from chance, Hays and his colleagues concluded that a substantial fraction of the climatic variation recorded in their cores was caused by variations in the Earth's orbit.

However, this linear version of the astronomical theory does not predict the 100,000-year cycle — a phenomenon which, at least over the last 500,000 years, is the dominant feature of climate. The origin of this cycle, and its possible link to the cycle of eccentricity, which has important components near a frequency of one cycle per 100,000 years, are questions now widely debated. One hypothesis — advanced by Hays and his co-workers and later developed by this author and John Z. Imbrie — attempts to explain the 100,000-year cycle as a nonlinear response of the climate system to the astronomical driving mechanism. When this model is applied to the astronomical curves, a theoretical climate-curve is obtained that exhibits a 100,000-year cycle and that mimics quite satisfactorily the isotopic curve of the last 250,000 years. Extended further back in time, the model begins to depart from the known climatic record. Extended into the future, this model predicts that the next ice age will reach its maximum extent in 23,000 years.

Clearly, this astronomical model of future climate ignores all frequencies higher than one cycle per 19,000 years — and fails to take anthropogenic effects (such as that produced by

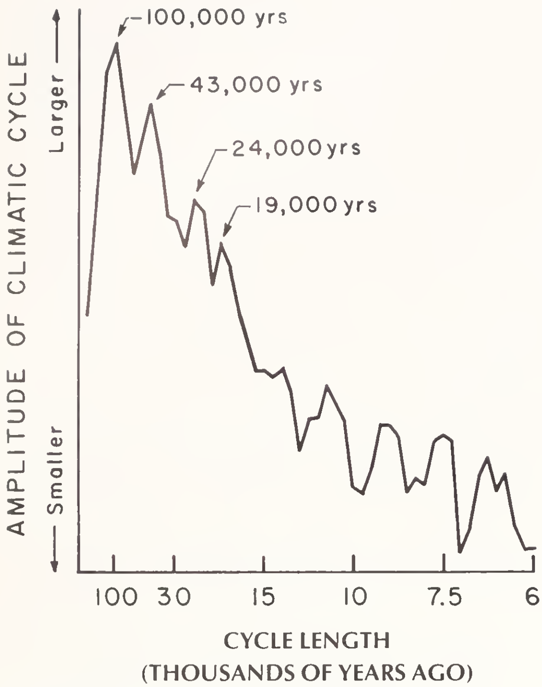

Figure 5. Spectrum of climatic variation over the half-million year-long record shown in Figure 3. This graph shows the relative importance of different cycles in this isotopic record of climate. (From Imbrie and Imbrie, 1979. Used with permission.)

carbon dioxide and discussed in the article by Peter Brewer (on page 12) into account. In Figure 6, an attempt is made to assess how the carbon dioxide effect might combine with an astronomically-driven cooling trend to yield a regime of warm climate extending over the next 3,000 years, followed by a slow cooling trend leading — some 23,000 years from now — to the maximum of the next ice age.

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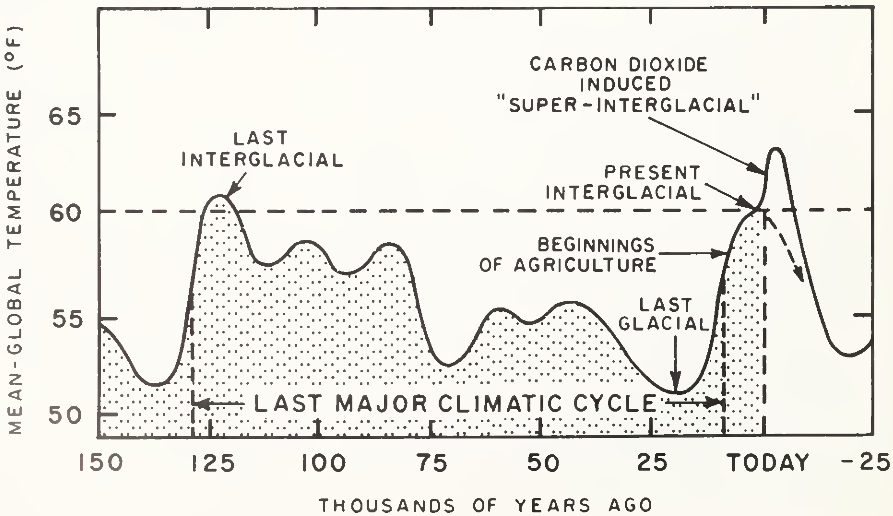
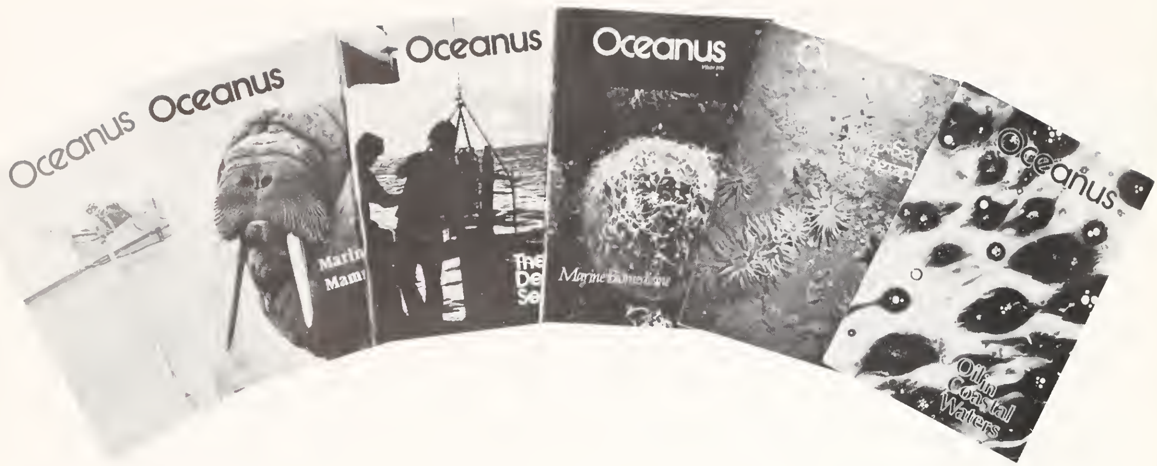


Figure 6. Climatic forecast for the next 25,000 years. According to one version of the astronomical theory of the ice ages, the natural course of future climate (shown by the dashed line) would be a cooling trend leading to full glacial conditions 23,000 years from now. The warming effect of carbon dioxide, however, may well interpose a "superinterglacial," with global mean temperatures reaching levels several degrees higher than those experienced at any time in the last million years. In that case, onset of a cooling trend leading to the next ice age would be delayed until the warming trend had run its course, perhaps 3,000 years from now (Modified from J. M. Mitchell, Jr., 1977b, and W. S. Broecker, 1975, by Imbrie and Imbrie, 1979. Used with permission.)

INDEX

VOLUME 21 (1978)



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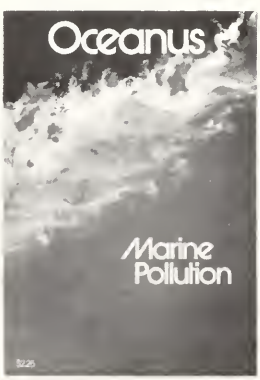

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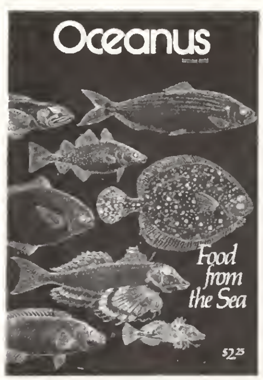

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